

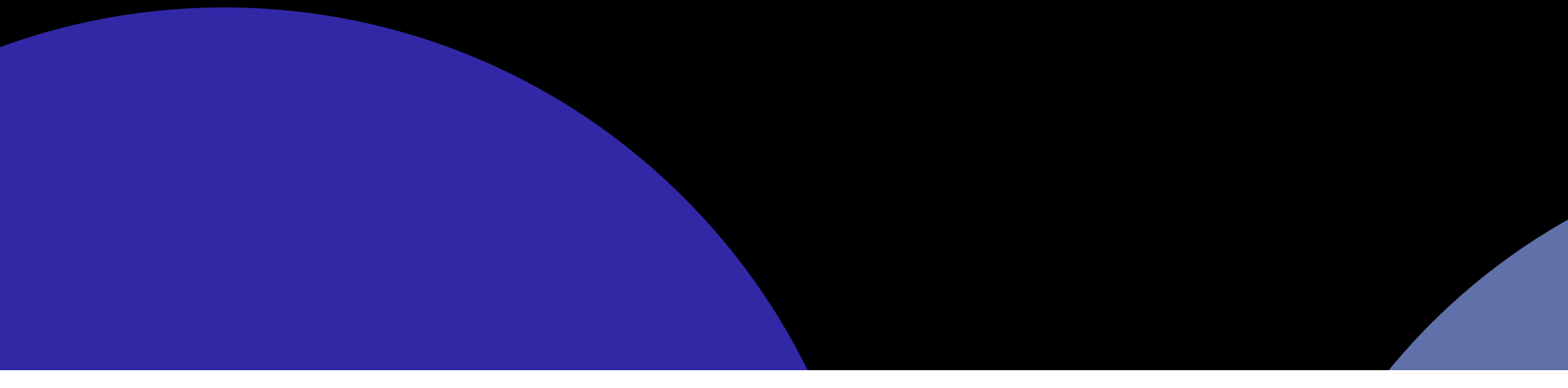
# THE ROAD FROM QCD TO NUCLEAR DOUBLE-BETA DECAYS

ZOHREH DAVOUDI

UNIVERSITY OF MARYLAND, MARYLAND CENTER FOR  
FUNDAMENTAL PHYSICS, AND RIKEN CENTER FOR  
ACCELERATOR-BASED SCIENCE

FERMILAB THEORY SEMINAR  
APRIL 2018

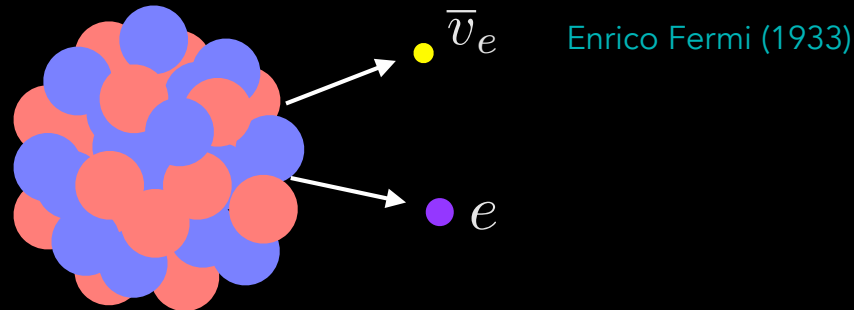
# 0 $\nu$ DOUBLE BETA DECAY AND BIG QUESTIONS

- IS LEPTON NUMBER CONSERVED?
  - WHAT IS THE NATURE OF NEUTRINO MASS?
  - WHAT NEW PHYSICS BEYOND SM IS SIGNIFIED BY THE OBSERVATION OF A LEPTON-NUMBER VIOLATING PROCESS?
- 

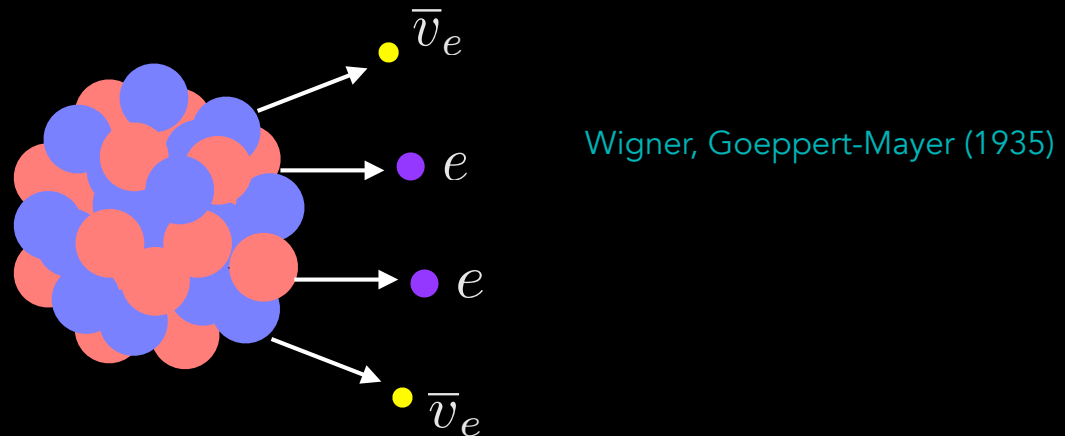
# 0V DOUBLE BETA DECAY AS A PROBE OF NEW PHYSICS

NEUTRINO OSCILLATIONS, SINGLE BETA DECAY AND COSMOLOGICAL CONSIDERATIONS SHED LIGHT ON THE NATURE OF NEUTRINOS. 0V DOUBLE BETA DECAY BY ITSELF PROVIDES A UNIQUE PROBE.

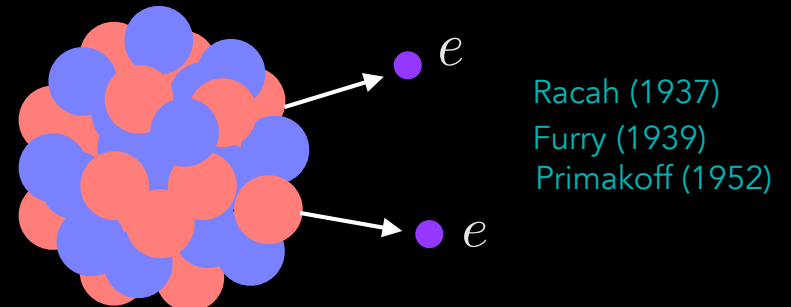
BETA DECAY:



DOUBLE-BETA DECAY:



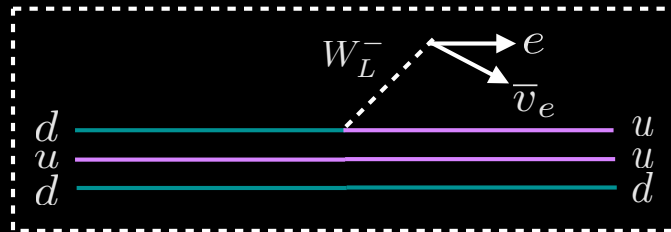
NEUTRINOLESS DOUBLE-BETA DECAY:



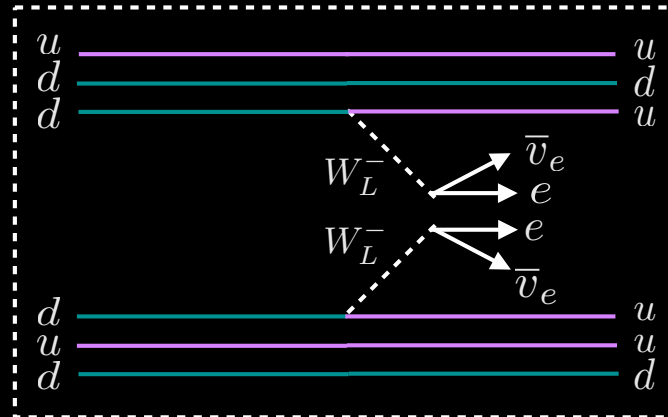
# 0V DOUBLE BETA DECAY AS A PROBE OF NEW PHYSICS

NEUTRINO OSCILLATIONS, SINGLE BETA DECAY AND COSMOLOGICAL CONSIDERATIONS SHED LIGHT ON THE NATURE OF NEUTRINOS. 0V DOUBLE BETA DECAY BY ITSELF PROVIDES A UNIQUE PROBE.

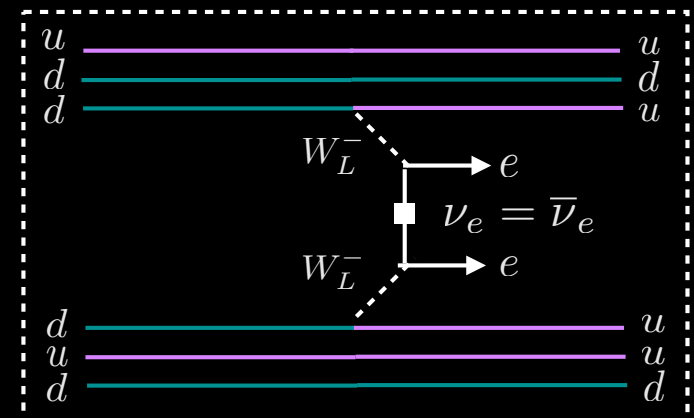
BETA DECAY:



DOUBLE-BETA DECAY:



NEUTRINOLESS DOUBLE-BETA DECAY:

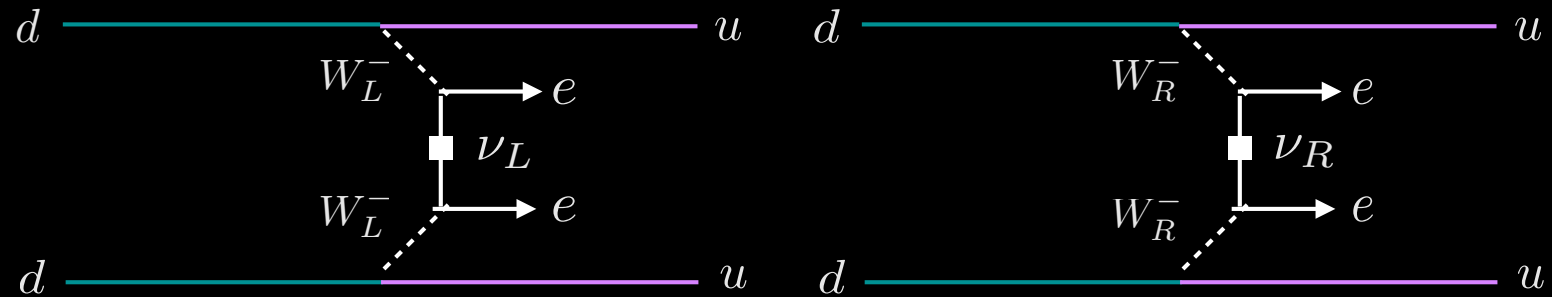


# POSSIBLE SCENARIOS...

## EXAMPLE: LEFT-RIGHT SYMMETRIC MODELS

Mohapatra, Pati, Senjanovic (1974-1975)

Mohapatra, Marshak (1979-1980)



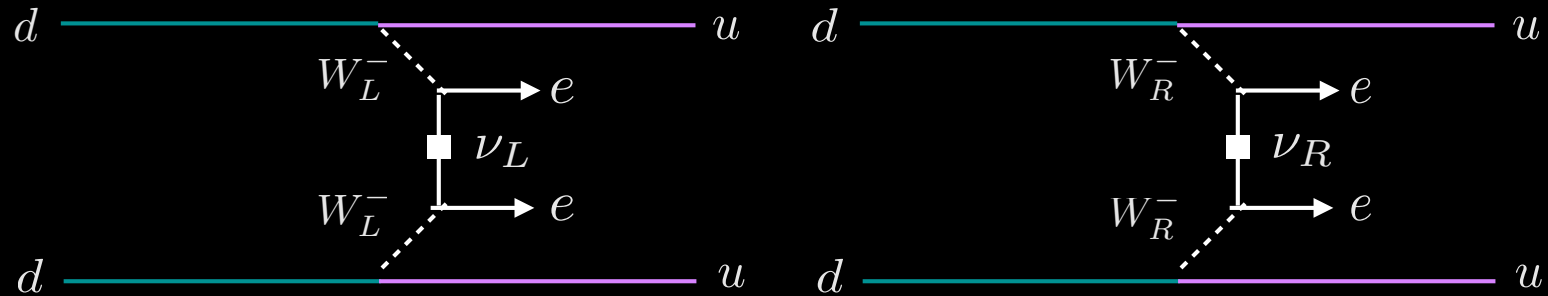
AND MANY MORE...

# POSSIBLE SCENARIOS...

## EXAMPLE: LEFT-RIGHT SYMMETRIC MODELS

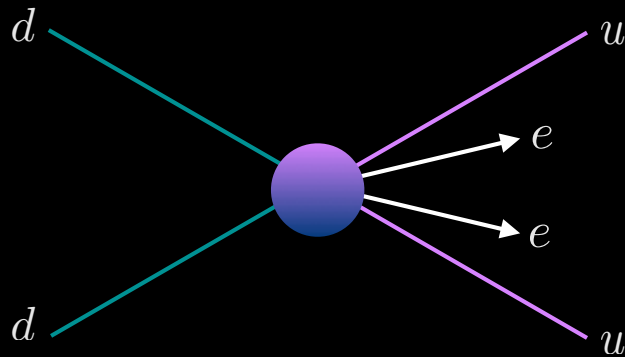
Mohapatra, Pati, Senjanovic (1974-1975)

Mohapatra, Marshak (1979-1980)



AND MANY MORE...

WITH ANY HIGH SCALE INVOLVED, A GENERAL EFFECTIVE INTERACTION IS:



$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^5} \bar{q} q \bar{q} q \bar{e}^c e$$

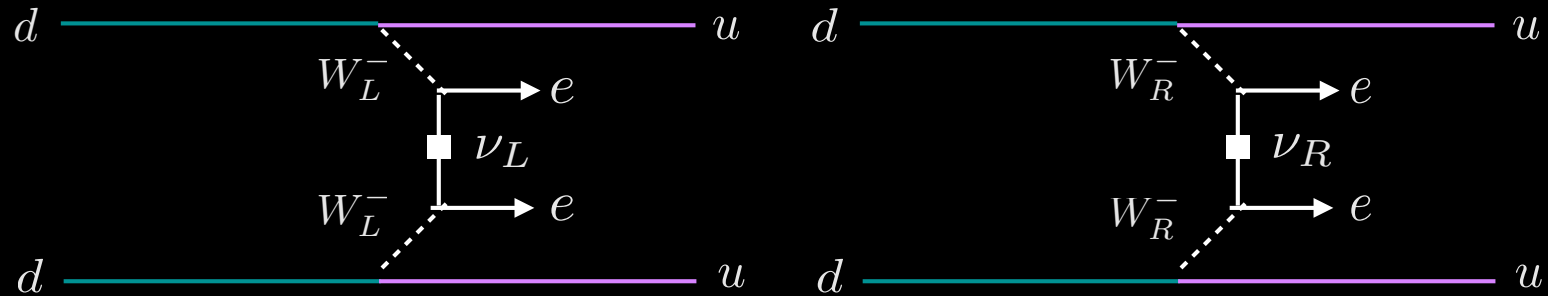
$$\Lambda \sim 1 \text{ TeV}$$

# POSSIBLE SCENARIOS...

## EXAMPLE: LEFT-RIGHT SYMMETRIC MODELS

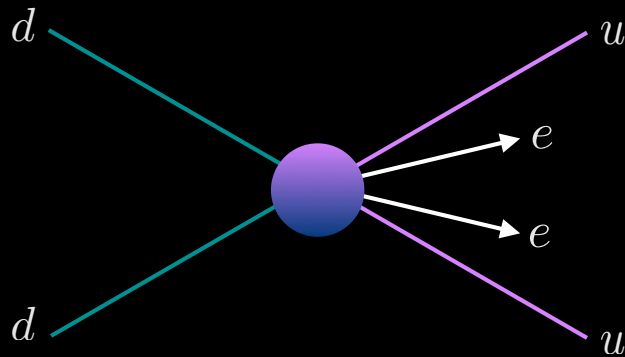
Mohapatra, Pati, Senjanovic (1974-1975)

Mohapatra, Marshak (1979-1980)



AND MANY MORE...

WITH ANY HIGH SCALE INVOLVED, A GENERAL EFFECTIVE INTERACTION IS:

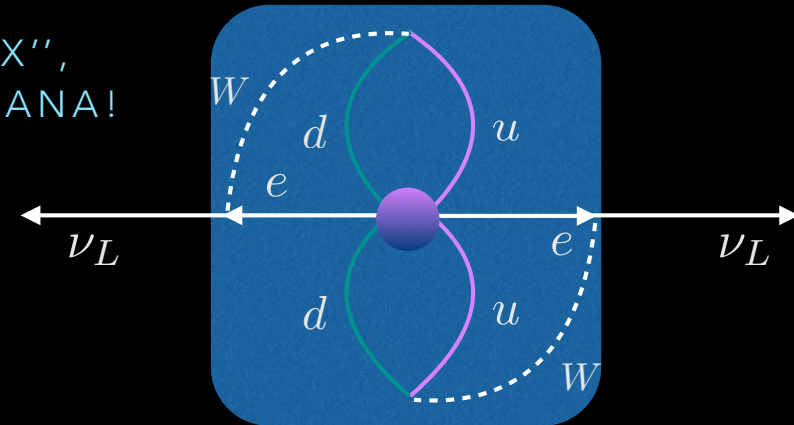


$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^5} \bar{q} q \bar{q} q \bar{e}^c e$$

$$\Lambda \sim 1 \text{ TeV}$$

AND NO MATTER WHAT GOES ON IN THE "BLACK BOX",  
WE HAVE ALREADY LEARNED NEUTRINOS ARE MAJORANA!

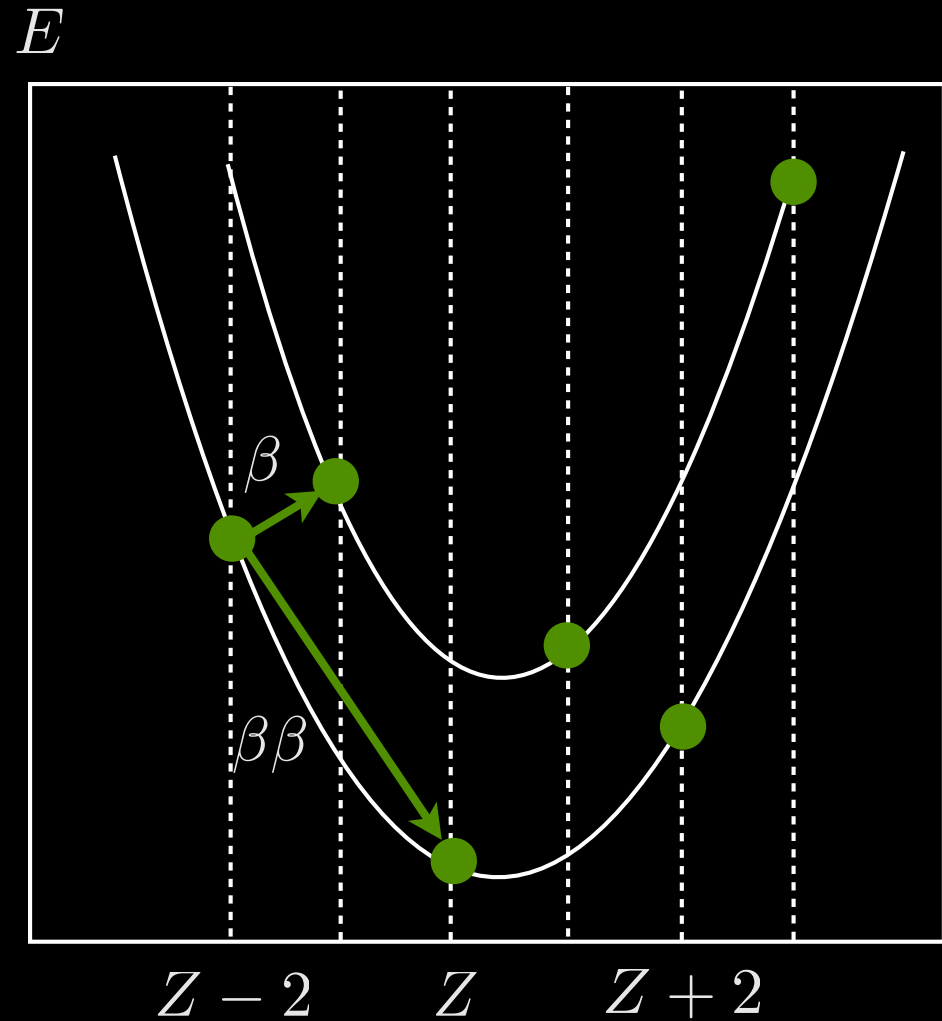
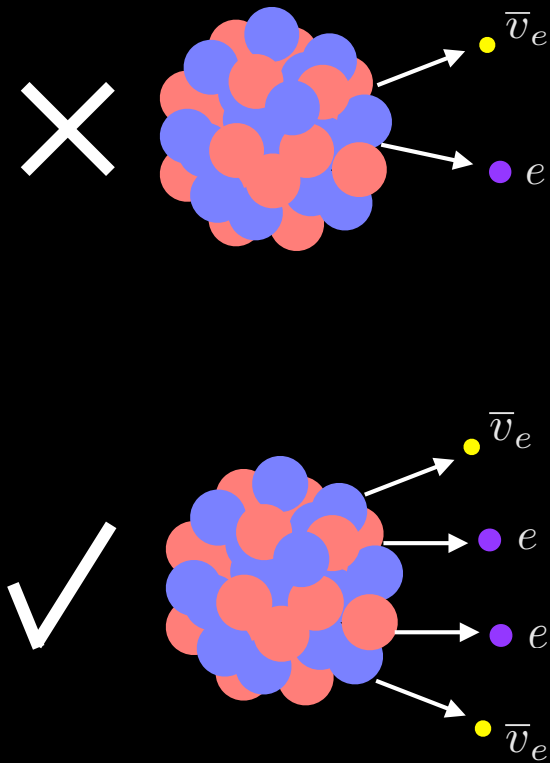
Schechter and Valle (1982)



HOW CAN SUCH A PROCESS BE DETECTED?

# NUCLEI PROVIDE A NATURAL LABORATORY

IN SOME INSTANCES SINGLE BETA DECAY FORBIDDEN AND  
THE DOMINANT DECAY MODE IS DOUBLE BETA DECAY



# NUCLEI PROVIDE A NATURAL LABORATORY

NOT MANY CHOICES AMONG NUCLEI

Periodic table from: <http://www.elementsdatabase.com/>

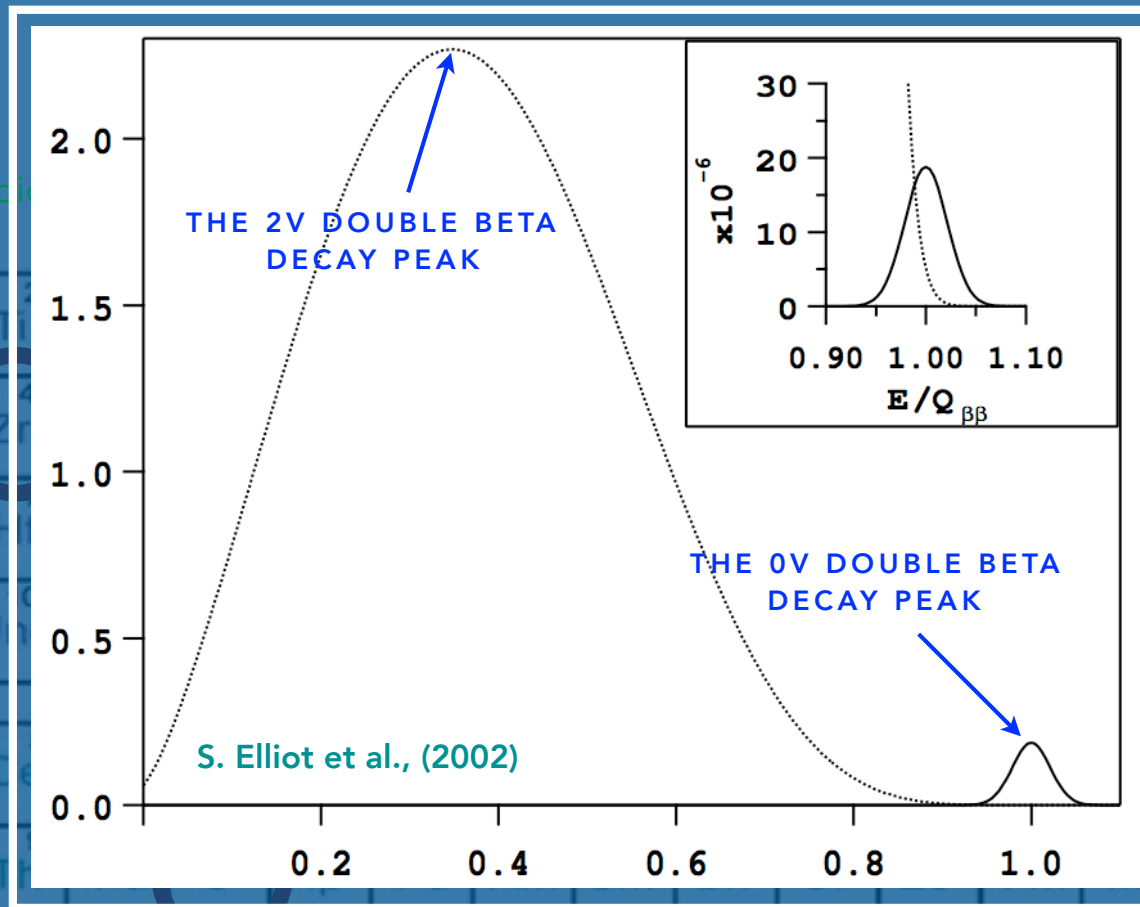
1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn									
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

SELECTION CRITERIA FOR EXPERIMENT:

1) Q VALUE, 2) ISOTOPIC ABUNDANCE, 3) NUCLEAR MATRIX ELEMENTS

# NUCLEI PROVIDE A NATURAL LABORATORY

## NOT MANY CHOICES AMONG NUCLEI



SELECTION CRITERIA FOR EXPERIMENT:

1) Q VALUE, 2) ISOTOPIIC ABUNDANCE, 3) NUCLEAR MATRIX ELEMENTS

# EXPERIMENTAL PROGRAM

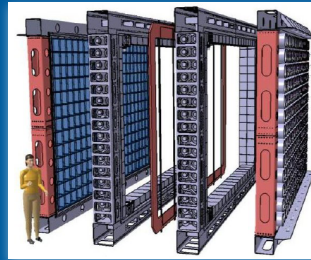
LOW BACKGROUND

Agostini, review talk at the KITP (2016)

BEST LIMITS

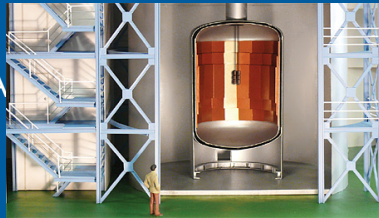
$$T_{1/2}^{0\nu}(^{76}\text{Ge}) > 5.2 \times 10^{25} \text{ yr}$$

$$T_{1/2}^{0\nu}(^{136}\text{Xe}) > 10.7 \times 10^{25} \text{ yr}$$



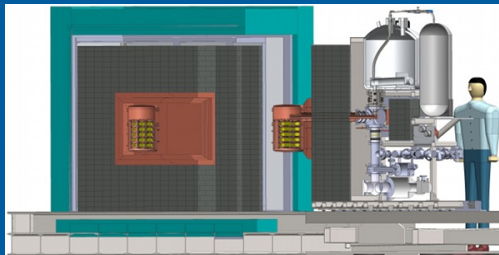
SUPERNEMO  
 $^{82}\text{Se}$

GERDA  
 $^{76}\text{Ge}$

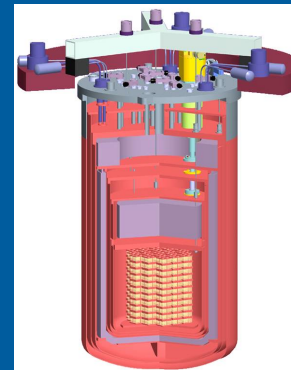


KAMLAND-ZEN  
EXO  
 $^{136}\text{Xe}$

MAJORANA



CUORE  
 $^{130}\text{Te}$



HIGH ENERGY RESOLUTION

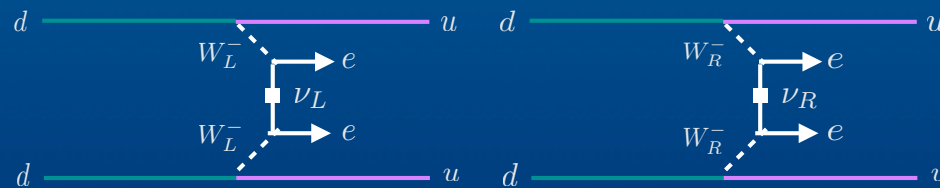
LARGE TARGET MASS

HOW TO CONNECT AN OBSERVED RATE IN  
NUCLEI TO THE FUNDAMENTAL THEORY?

# BOTTOM-UP APPROACH: MATCHING THE HIGH SCALE TO LOW SCALE

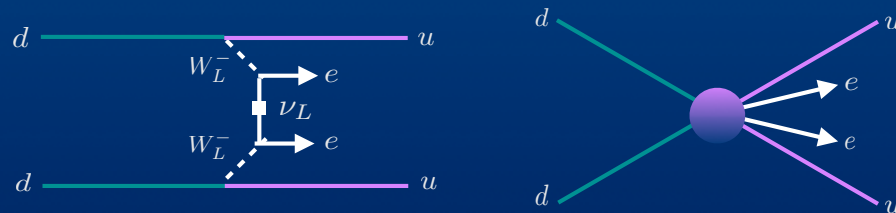
$$\Lambda > \text{TeV}$$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



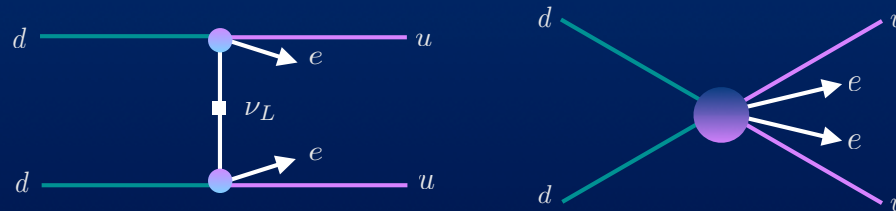
$$\Lambda \sim 10^2 \text{ GeV}$$

RUN IT DOWN TO BELOW THE EW SYMMETRY BREAKING SCALE:



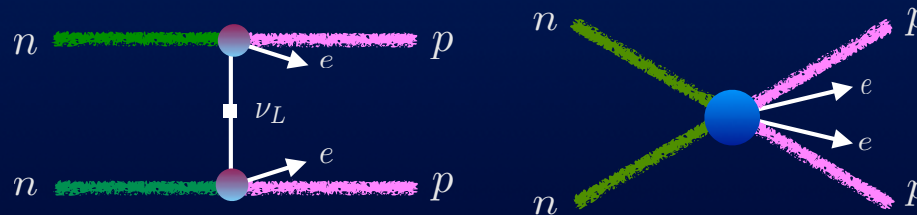
$$\Lambda \sim 2 \text{ GeV}$$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



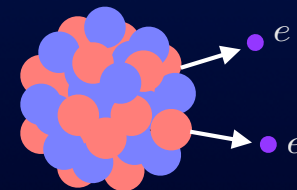
$$\Lambda < \text{GeV}$$

RUN IT DOWN TO THE HADRONIC SCALE:



$$\Lambda < \text{MeV}$$

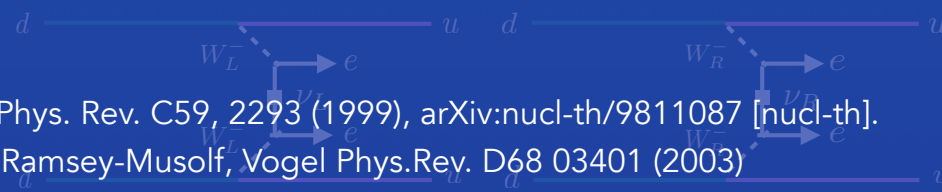
USE NUCLEAR MANY-BODY CALCULATION TO  
MATCH IT TO NUCLEAR MATRIX ELEMENTS:



# MOST PARAMETERS EXCEPT FOR FEW ALREADY PRESENT IN STANDARD MODEL

$$\Lambda > \text{TeV}$$

START WITH YOUR FAVORITE HIGH-SCALE MODEL, E.G.:



Savage, Phys. Rev. C59, 2293 (1999), arXiv:nucl-th/9811087 [nucl-th].

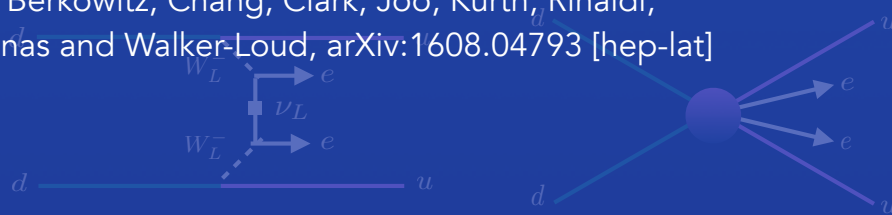
Prezeau, Ramsey-Musolf, Vogel Phys.Rev. D68 03401 (2003)

Cirigliano, Dekens, Graesser and Mereghetti, arXiv:1701.01443 [hep-ph].

$$\Lambda \sim 10^2 \text{ GeV}$$

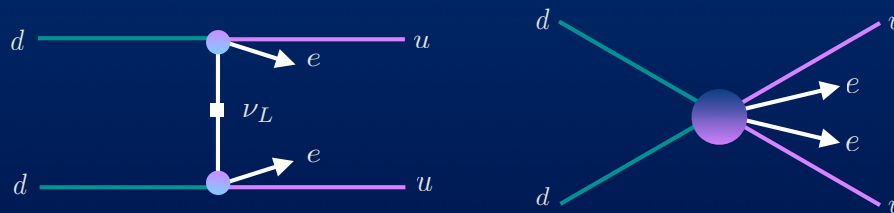
RUN IT DOWN TO BELOW THE EW SYMMETRY BREAKING SCALE:

Nicholson, Berkowitz, Chang, Clark, Joo, Kurth, Rinaldi,  
Tiburzi, Vranas and Walker-Loud, arXiv:1608.04793 [hep-lat]



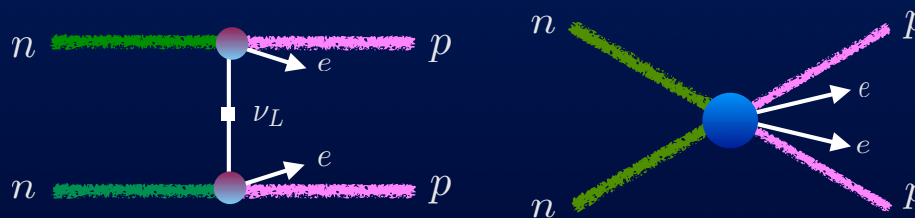
$$\Lambda \sim 2 \text{ GeV}$$

RUN IT DOWN TO PERTURBATIVE QUARK-LEVEL MATRIX ELEMENTS:



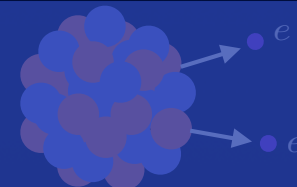
$$\Lambda < \text{GeV}$$

RUN IT DOWN TO THE HADRONIC SCALE:



$$\Lambda < \text{MeV}$$

USE NUCLEAR MANY-BODY CALCULATION TO  
MATCH IT TO NUCLEAR MATRIX ELEMENTS:



WHY IS THE LIGHT NEUTRINO SCENARIO  
MOTIVATED? WHAT MAY WE LEARN FROM  
A POTENTIAL OBSERVATION?

# SO THE LIGHT NEUTRINO SCENARIO IS INTERESTING IN LIGHT OF OTHER NEUTRINO EXPERIMENTS

NEUTRINOS HAVE MASS AND  
OSCILLATE INTO EACH OTHER!

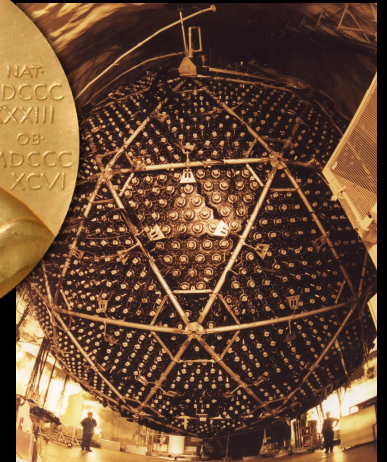
$$m_2^2 - m_1^2$$

$$|m_3^2 - m_2^2|$$

MIXING MATRIX U



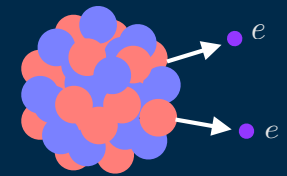
KamiokaNDE



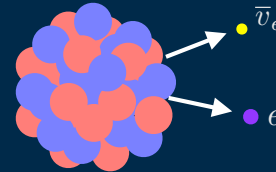
SNO

ABSOLUTE VALUES CAN BE CONSTRAINED BY:

$$\langle m_{\beta\beta} \rangle = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 |U_{e3}|^2 e^{-i(\alpha_1 + 2\delta)} \right|$$



$$\langle m_{\beta} \rangle^2 = m_1^2 |U_{e1}|^2 + m_2^2 |U_{e2}|^2 + m_3^2 |U_{e3}|^2$$

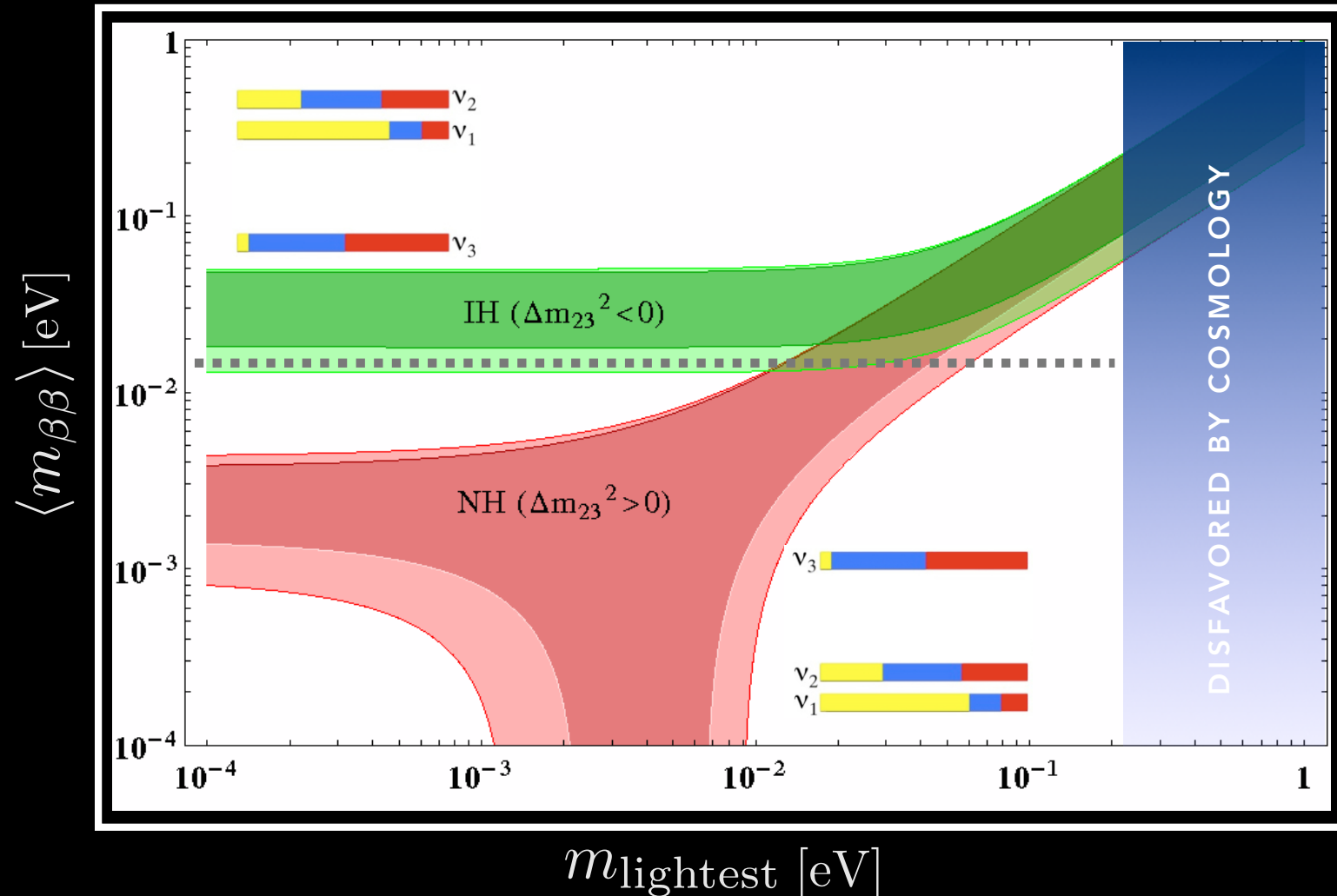


$$\Sigma = m_1 + m_2 + m_3$$



# THE LIGHT NEUTRINO SCENARIO IS WELL MOTIVATED IN LIGHT OF OTHER NEUTRINO EXPERIMENTS

DOTTED LINE IS THE REACH OF A TON-SCALE EXPERIMENT.



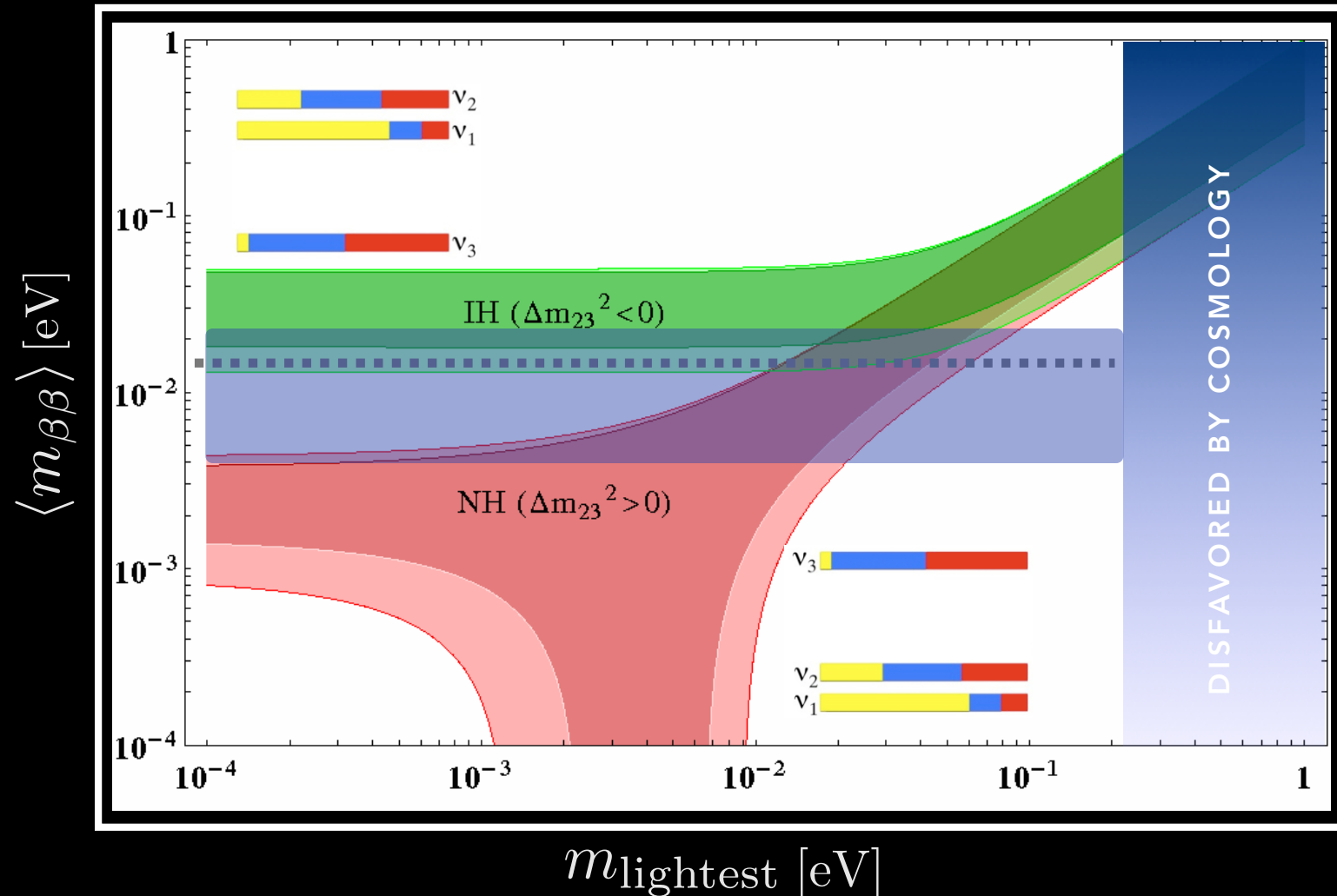
DISCOVERY IS POSSIBLE WITHIN THIS SCENARIO IF SPECTRUM IS  
INVERTED OR IF THE LIGHTEST MASS IS GREATER THAN  $\sim 50$  meV.

Dell'Oro, Marcocci, Viel and Vissani, Advances in High Energy Physics, Volume 2016 (2016)

Carolina Lujan-Peschar, Giulia Pagliaroli, Francesco Vissani, Eur.Phys.J. C73 (2013) 2439

# THE LIGHT NEUTRINO SCENARIO IS WELL MOTIVATED IN LIGHT OF OTHER NEUTRINO EXPERIMENTS

DOTTED LINE IS THE REACH OF A TON-SCALE EXPERIMENT.



DISCOVERY IS POSSIBLE WITHIN THIS SCENARIO IF SPECTRUM IS  
INVERTED OR IF THE LIGHTEST MASS IS GREATER THAN  $\sim 50$  meV.

Dell'Oro, Marcocci, Viel and Vissani, Advances in High Energy Physics, Volume 2016 (2016)

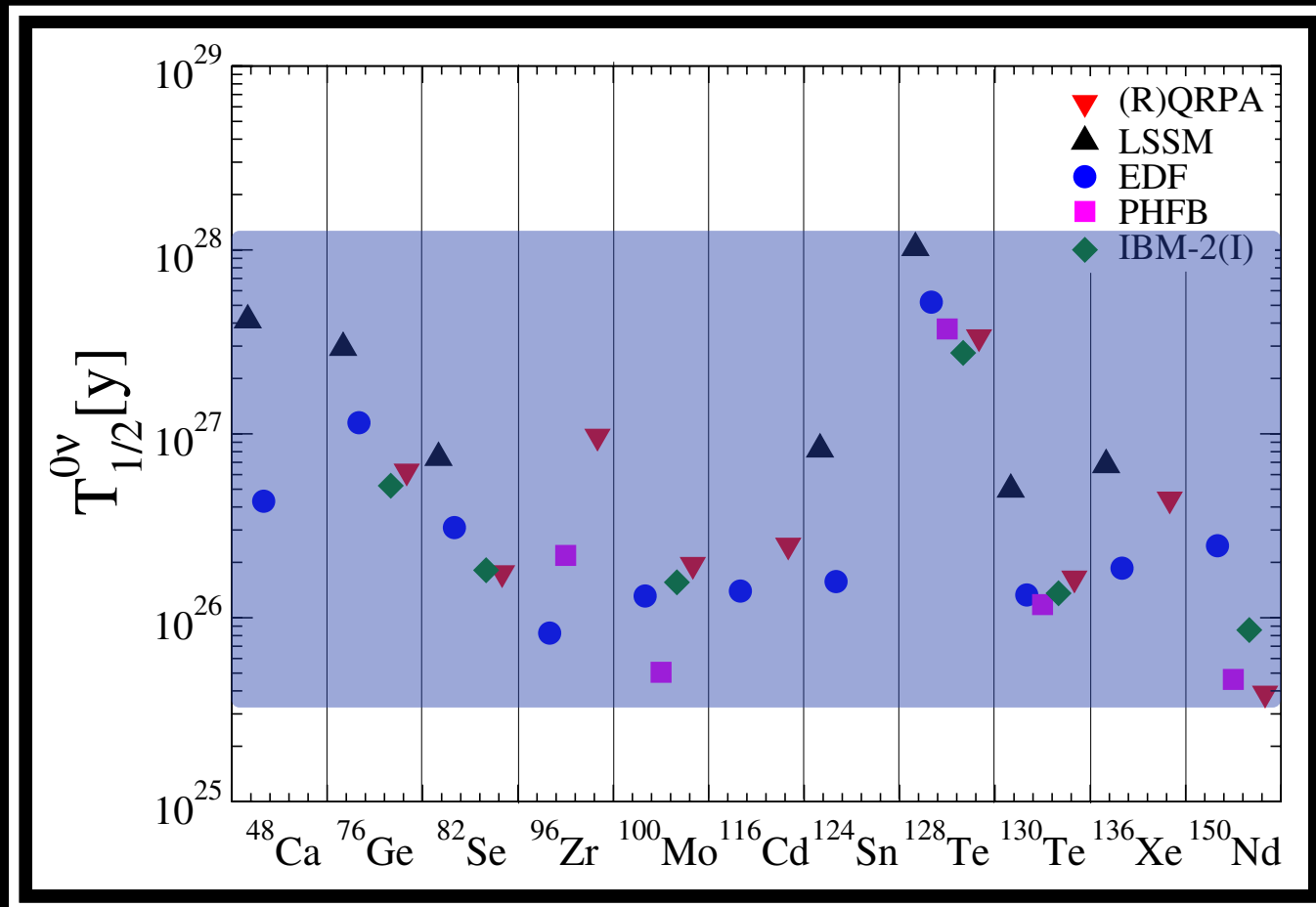
Carolina Lujan-Peschar, Giulia Pagliaroli, Francesco Vissani, Eur.Phys.J. C73 (2013) 2439

# CURRENT STATUS OF NUCLEAR MATRIX ELEMENTS

## DECAY RATE

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

NUCLEAR MATRIX ELEMENT IN LIGHT  
NEUTRINO EXCHANGE SCENARIO

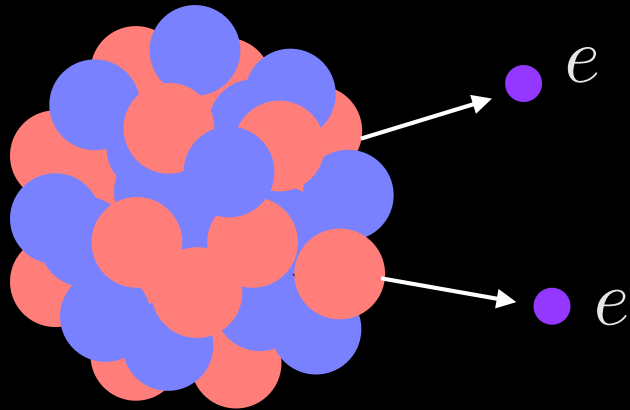


Avignone, Elliott and Engel, REVIEWS OF MODERN PHYSICS, VOLUME 80 (2008)

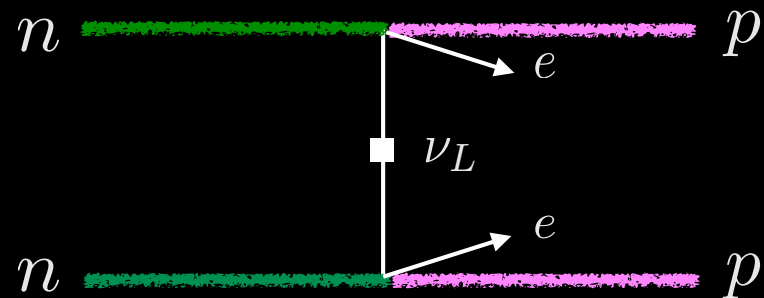
Vergados, Ejiri and Simkovic, Rep. Prog. Phys. 75 106301 (2012)

Menendez, Gazit, and Schwenk, Phys.Rev.Lett.107, 062501 (2011)

# $nn - pp$ TRANSITION FROM FIRST PRINCIPLES



MOMENTUM EXCHANGED:  $q \sim 100$  MeV  
THREE AND MULTI-NUCLEON EFFECTS?



BUT NATURE DOES NOT PROVIDE US WITH THE NNPP TRANSITION RATE!  
HOW THEN MAY ONE DETERMINE THE LOW-ENERGY CONSTANTS INVOLVED?

# LATTICE QCD INPUT FOR THE AMPLITUDE

PACS-CS Collaboration, Yamazaki, Kuramashi and Ukawa, Phys.Rev. D81 (2010) 111504.

Yamazaki, Ishikawa, Kuramashi and Ukawa, Phys.Rev. D86 (2012) 074514.

Yamazaki, Ishikawa, Kuramashi and Ukawa, arXiv:1502.0418.

HALQCD Collaboration, Inoue et. al., Nucl. Phys. A881 (2012) 28–43.

Orginos, et al. [NPLQCD collaboration], Phys. Rev. D 92, 114512 (2015).

Berkowitz, et al. [CalLatt collaboration], arXiv:1508.00886 [hep-lat].

+

# THE AMPLITUDE IN EFFECTIVE FIELD THEORY

Pionless EFT for few nucleon systems:

Kaplan, Savage, and Wise, Phys. Lett., B424, 390 (1998)

Kaplan, Savage, and Wise, Nucl. Phys., B534, 329 (1998)

Chen, Rupak and Savage, Nucl. Phys. A 653, 386 (1999)

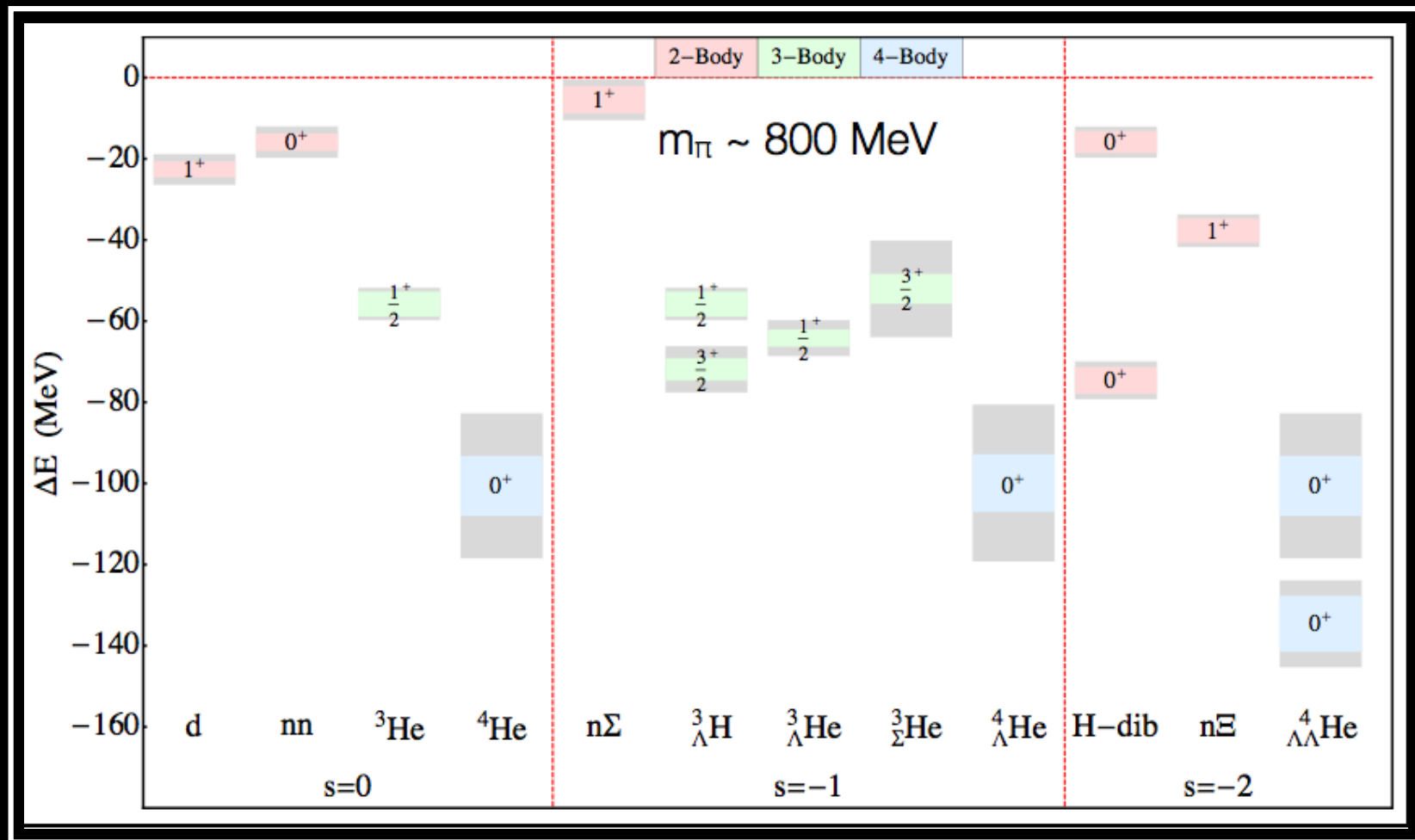
Beane, Bedaque, Savage and van Kolck, Nucl.Phys.A700 (2002)

Bedaque, Hammer and van Kolck, Phys.Rev.Lett. 82 (1999)

De-Leon, Platter and Gazit, arXiv:1611.10004 [nucl-th]. (2016)

Chiral two-body currents in nuclei: Gamow-Teller transitions and neutrinoless double-beta decay: Menéndez, Gazit and Schwenk, Phys.Rev.Lett.107:062501 (2011).

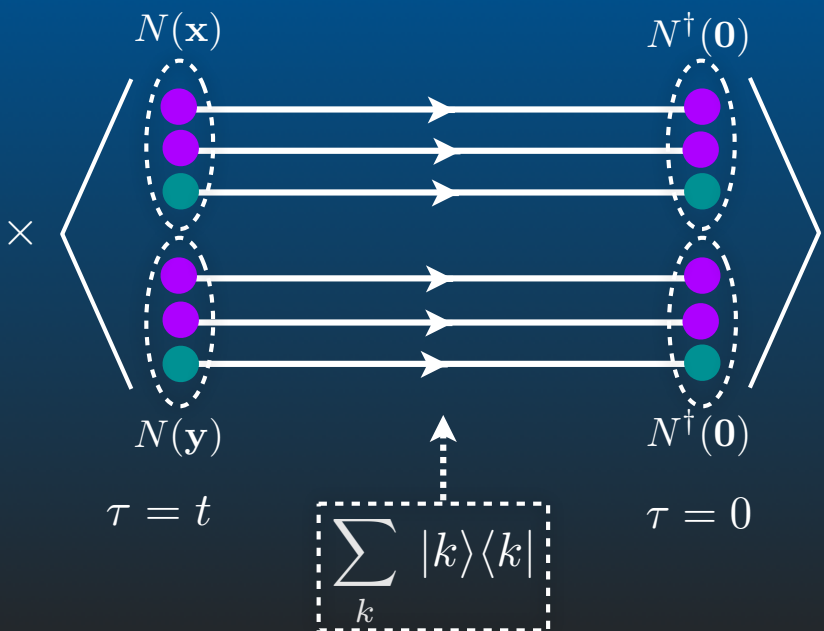
# NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS



Beane, et al. (NPLQCD), Phys.Rev. D87 (2013) , Phys.Rev. C88 (2013)

Barnea, Contessi, Gazit, Pederiva and van Kolck, Phys.Rev.Lett. 114, 052501 (2015).

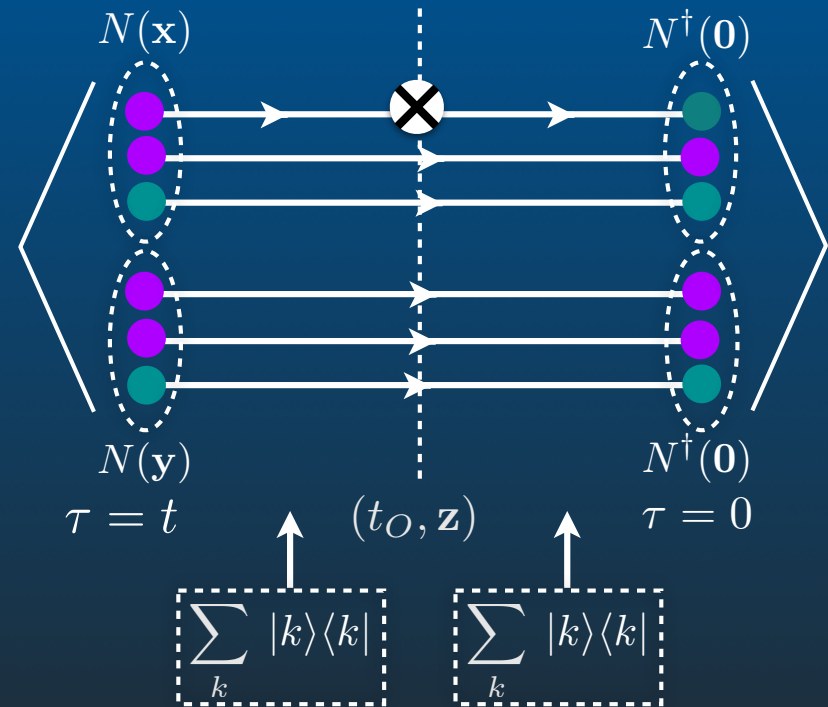
# LATTICE QCD TWO-POINT CORRELATION FUNCTIONS AND ENERGY SPECTRA

$$C(\mathbf{P}; t) = \sum_{\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{P}} \sum_{\mathbf{x}, \mathbf{y}} e^{i\mathbf{p}_1 \cdot \mathbf{x} + i\mathbf{p}_2 \cdot \mathbf{y}} \times$$


$$= Z_0^{\text{src}} Z_0^{\text{snk}\dagger} e^{-E_0 t} + \dots$$

# LATTICE QCD THREE-POINT CORRELATION FUNCTIONS AND MATRIX ELEMENTS

$$C(\mathbf{P}; t, t_O) = \sum_{\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{P}} \sum_{\mathbf{x}, \mathbf{y}, \mathbf{z}} e^{i\mathbf{p}_1 \cdot \mathbf{x} + i\mathbf{p}_2 \cdot \mathbf{y}} \times$$



$$= Z_{0,pp}^{\text{src}} Z_{0,d}^{\text{snk}\dagger} e^{-E_{0,pp}t_O} e^{-E_{0,d}(t-t_O)} \langle pn | A | pp \rangle_L + \dots$$

# BACKGROUND FIELDS ARE ALTERNATIVE: A NEW IMPLEMENTATION

$$S_{\lambda_q; \Gamma}^{(q)}(x, y) = S^{(q)}(x, y) + \lambda_q \int dz S^{(q)}(x, z) \Gamma S^{(q)}(z, y)$$

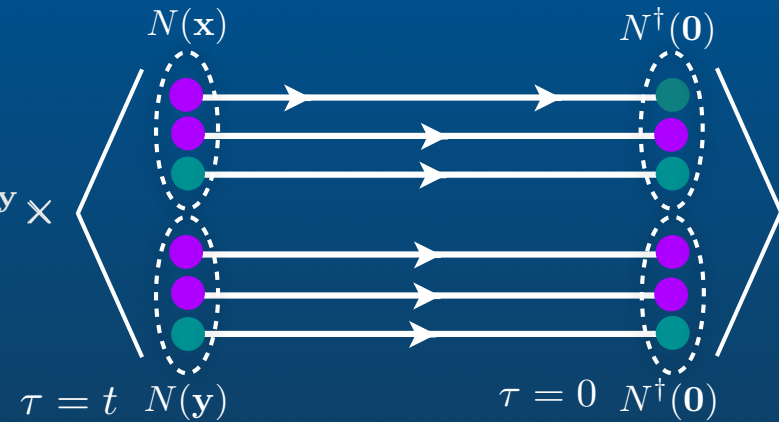


Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold  
and Orginos, (NPLQCD collaboration), Phys.Rev.Lett.119,062002(2017),  
arXiv:1610.04545 [hep-latt].

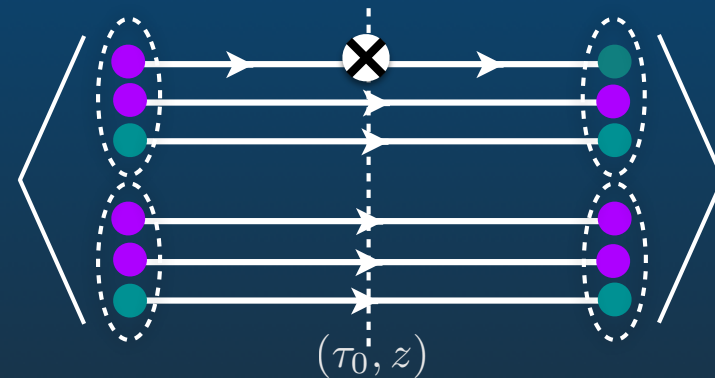
Buochard, Bouchard, Chang, Kurth, Orginos and Walker-Loud,  
Phys.Rev.D96,014504(2017), arXiv:1612.06963 [hep-lat].

# BACKGROUND FIELDS ARE ALTERNATIVE: A NEW IMPLEMENTATION

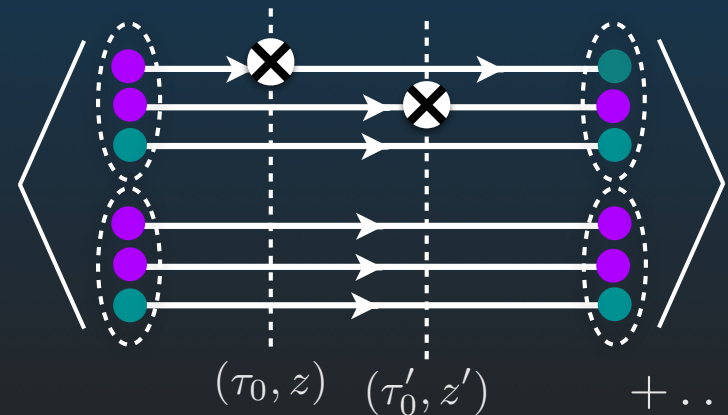
$$C_{\lambda}(\mathbf{P}; t, t_0) = \sum_{\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{P}} \sum_{\mathbf{x}, \mathbf{y}, \mathbf{z}} e^{i\mathbf{p}_1 \cdot \mathbf{x} + i\mathbf{p}_2 \cdot \mathbf{y}} \times$$



$$+ \sum_{\tau_0=0}^T \sum_z$$

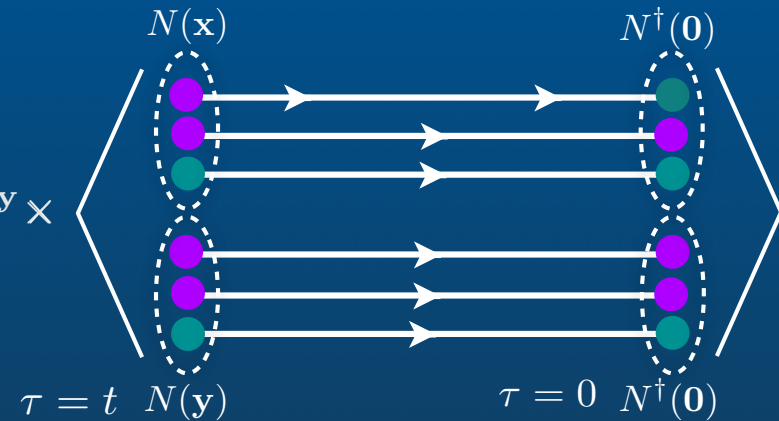


$$+ \sum_{\tau_0=0}^T \sum_{\tau'_0=0}^T \sum_z \sum_{z'}$$



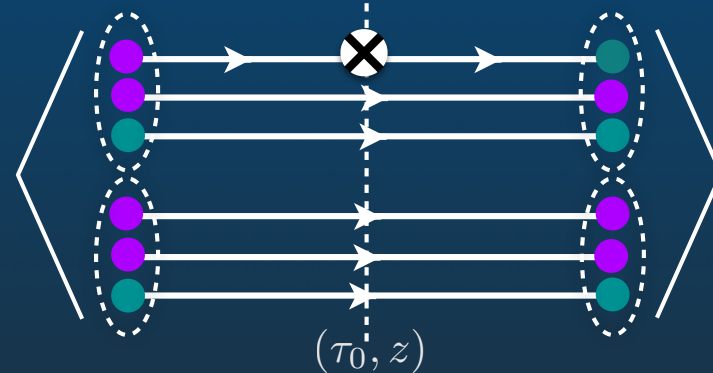
# BACKGROUND FIELDS ARE ALTERNATIVE: A NEW IMPLEMENTATION

$$C_{\lambda}(\mathbf{P}; t, t_0) = \sum_{\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{P}} \sum_{\mathbf{x}, \mathbf{y}, \mathbf{z}} e^{i\mathbf{p}_1 \cdot \mathbf{x} + i\mathbf{p}_2 \cdot \mathbf{y}} \times$$



ALL  
POSSIBILITIES  $\longrightarrow$

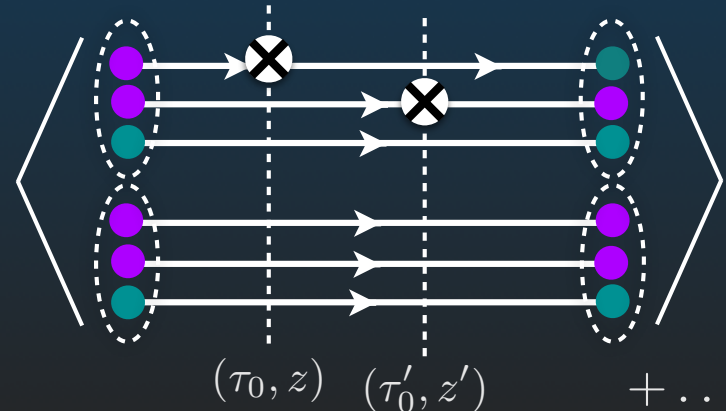
$$+ \sum_{\tau_0=0}^T \sum_z$$



TIME-ORDERED  
PRODUCT  $\downarrow$

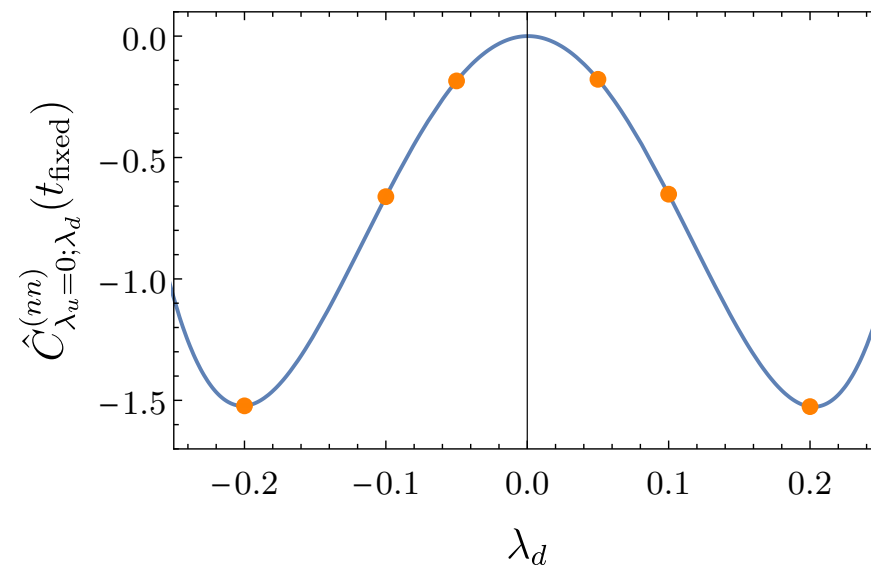
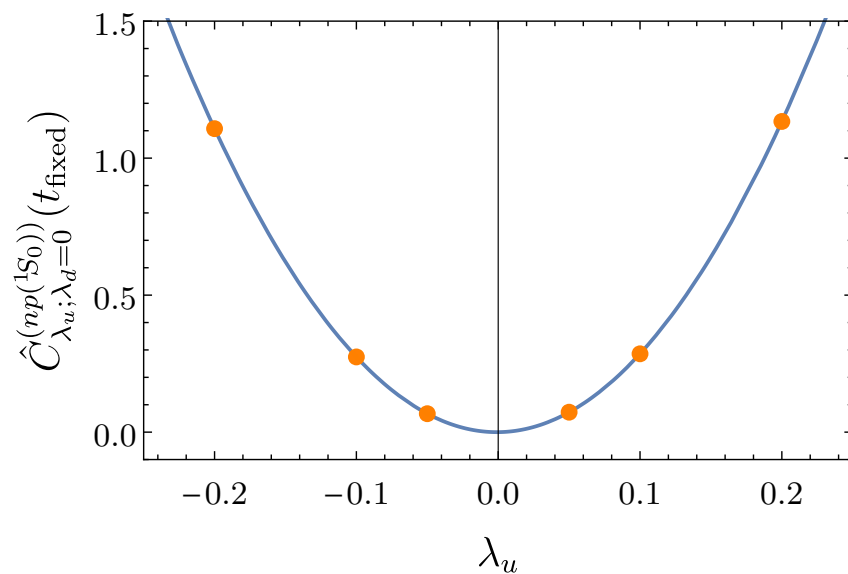
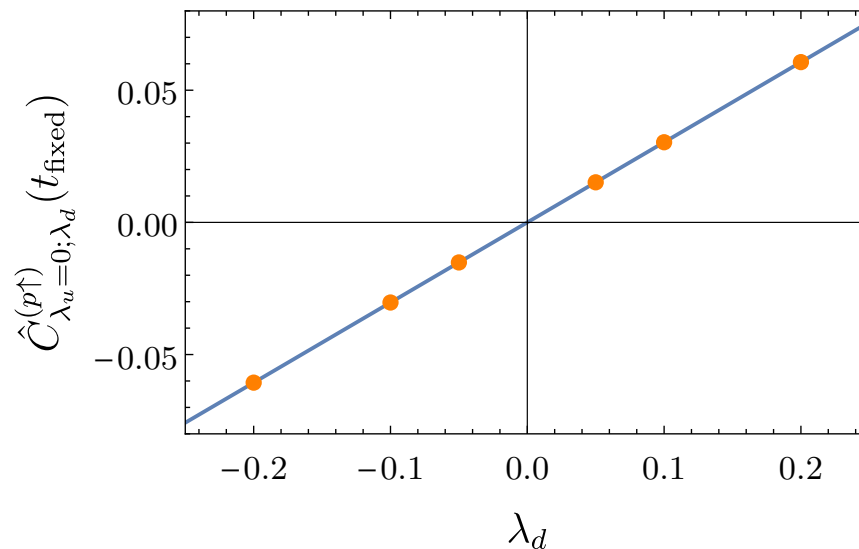
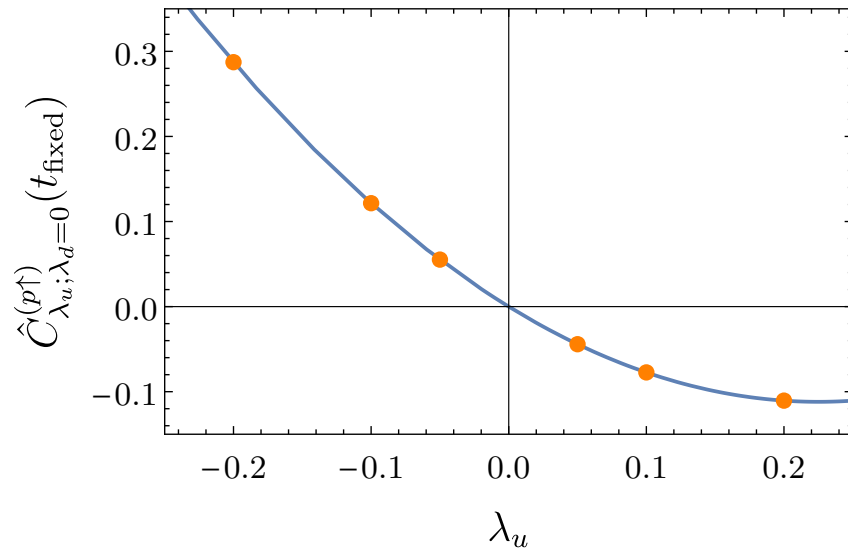
ALL  
POSSIBILITIES  $\longrightarrow$

$$+ \sum_{\tau_0=0}^T \sum_{\tau'_0=0}^T \sum_z \sum_{z'}$$

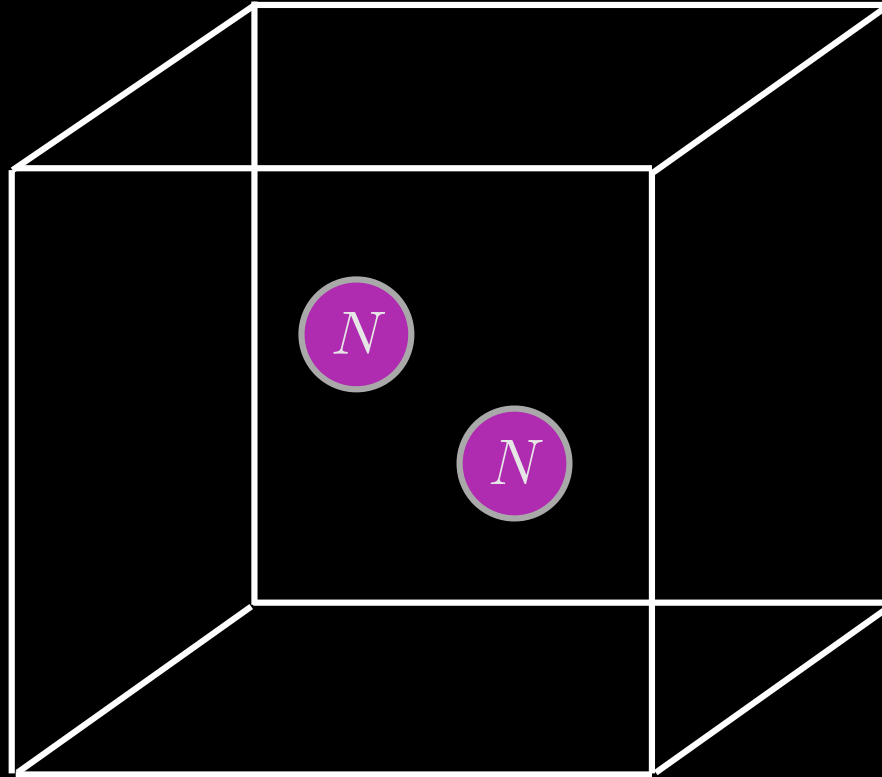


DOUBLE-CURRENT MES ARE EXACT  
FOR ISOTENSOR QUANTITIES.

# BACKGROUND FIELDS ARE ALTERNATIVE: A NEW IMPLEMENTATION

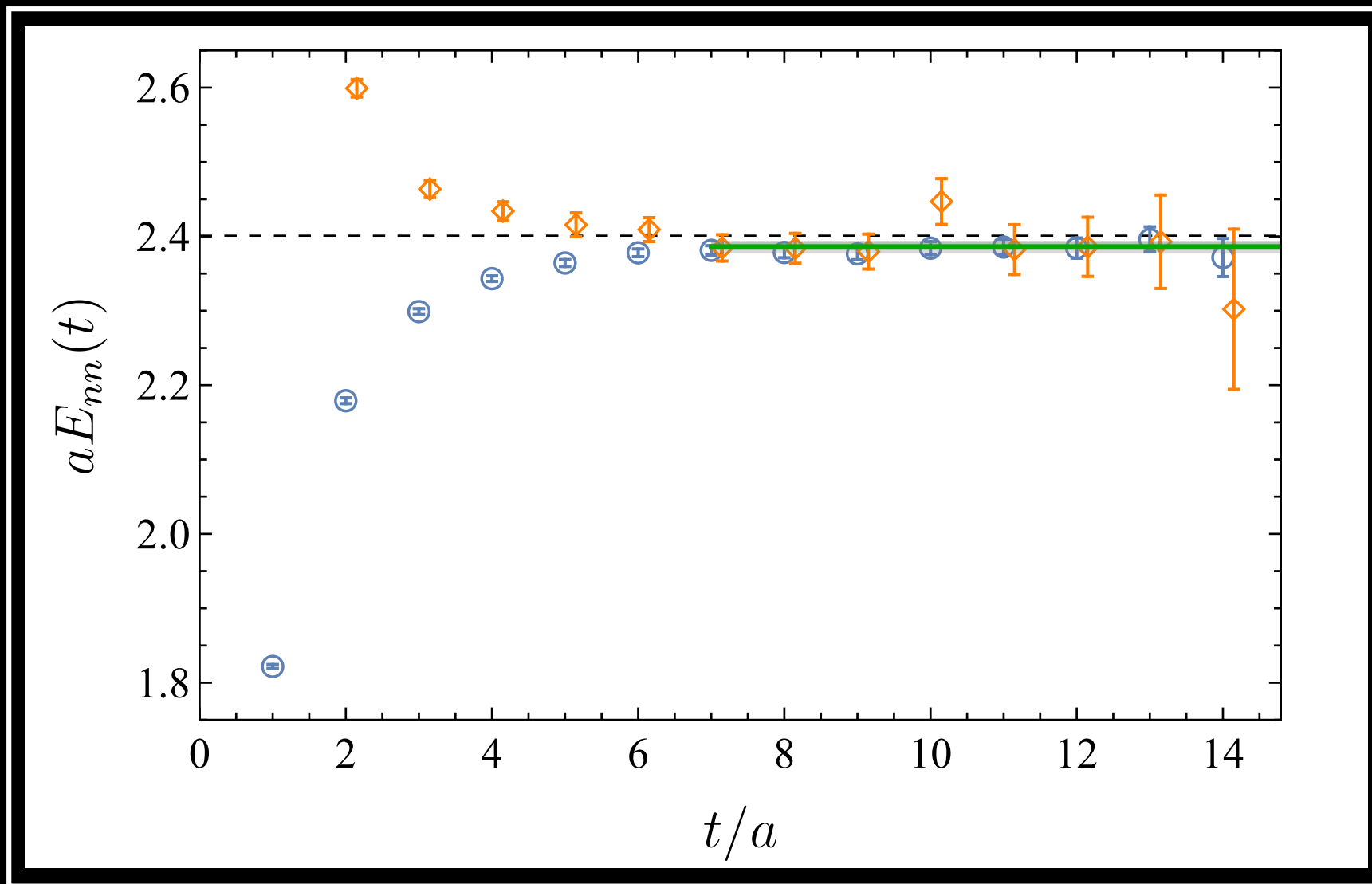


# NO BACKGROUND FIELD



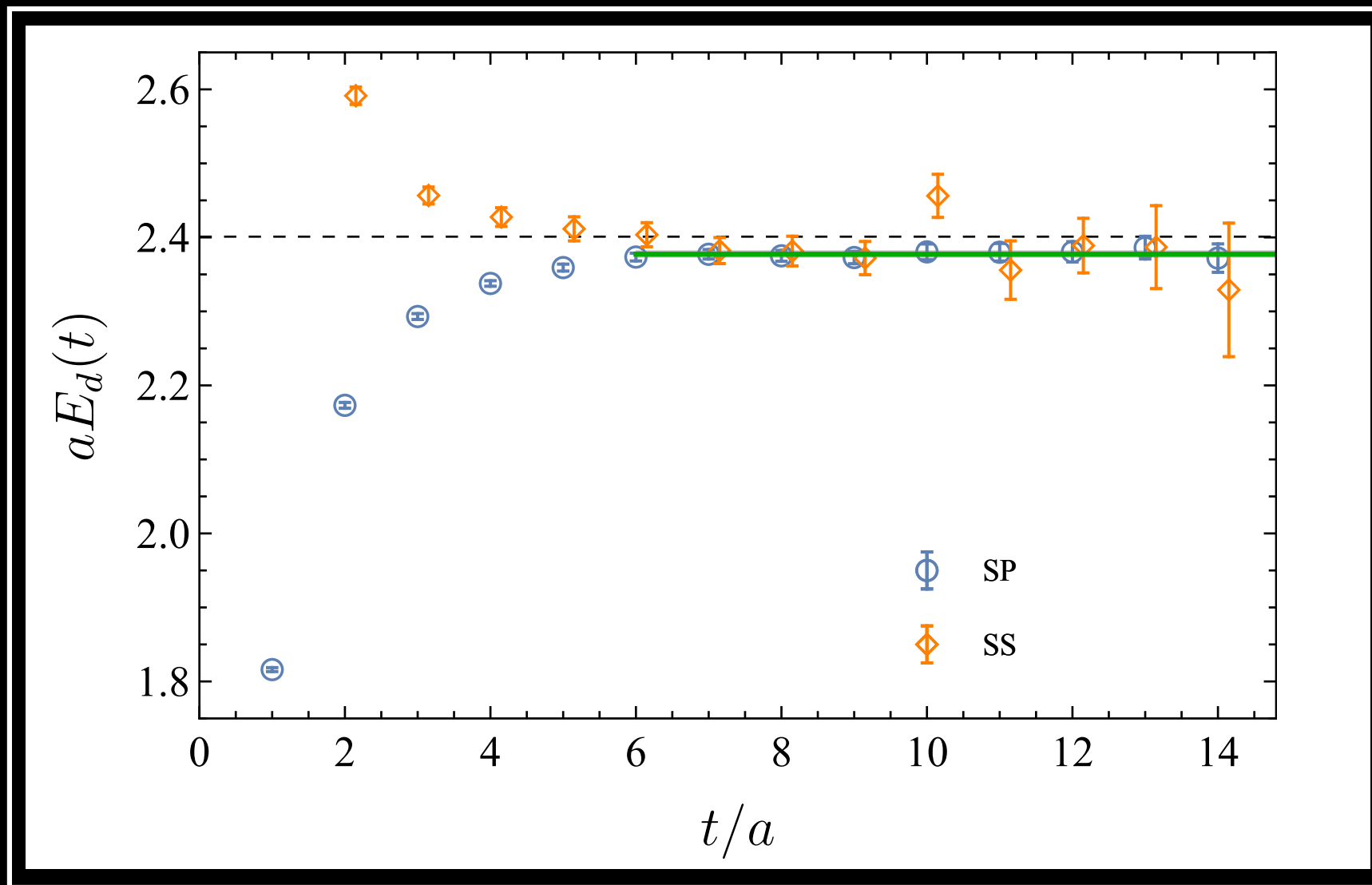
Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos, Savage, Shanahan (NPLQCD collaboration),  
arXiv:1610.04545 [hep-latt], arXiv:1701.03456 [hep-lat], arXiv:1701.03456 [hep-lat], arXiv:1702.02929 [hep-lat].

# NO BACKGROUND FIELD



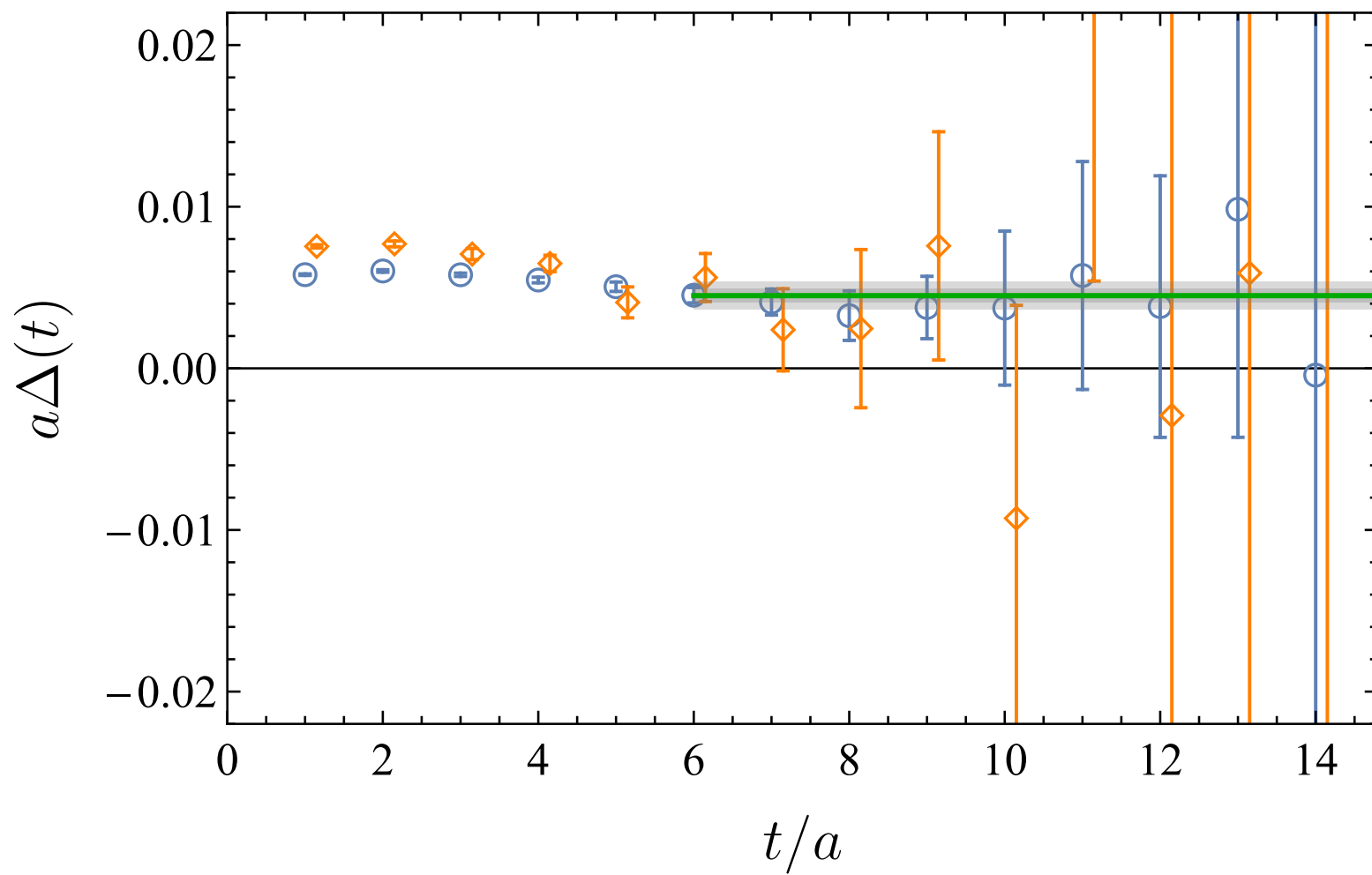
@  $m_\pi \approx 800$  MeV

# NO BACKGROUND FIELD



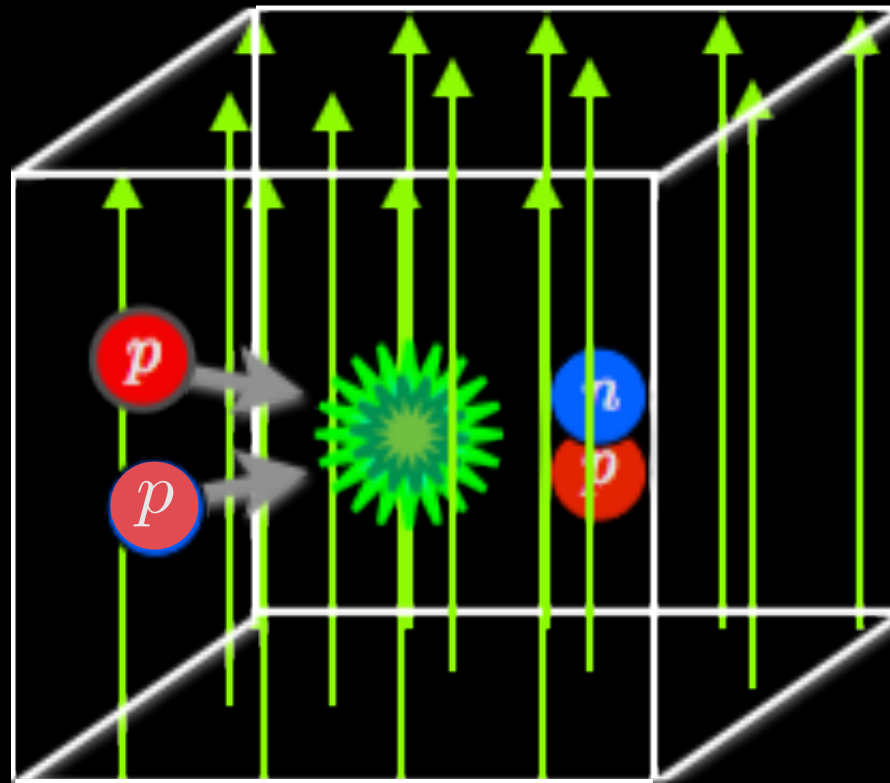
@  $m_\pi \approx 800$  MeV

# NO BACKGROUND FIELD



@  $m_\pi \approx 800$  MeV

# FIRST-ORDER RESPONSE TO AXIAL FIELD

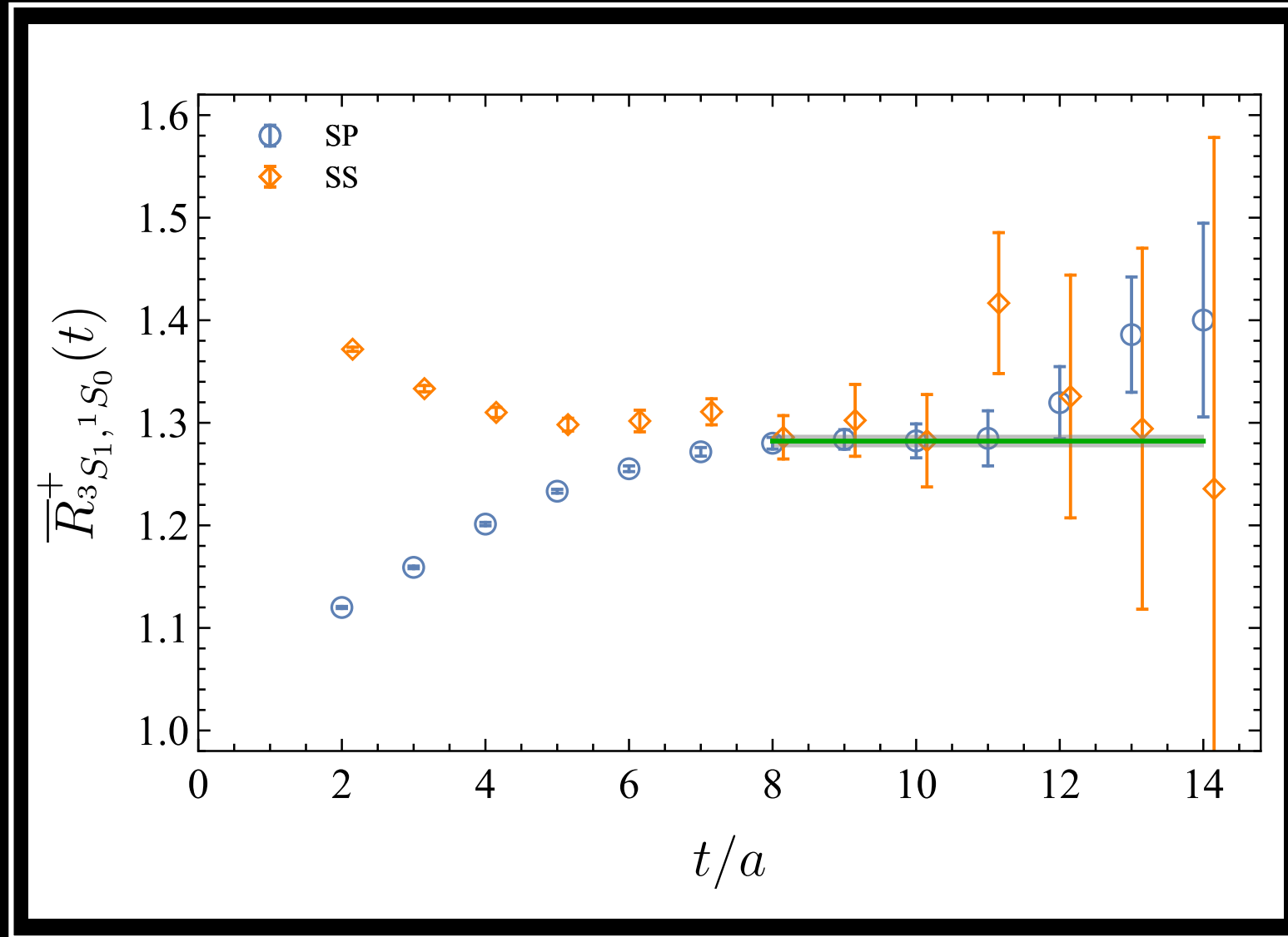


Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold  
and Orginos, (NPLQCD collaboration), Phys.Rev.Lett.119,062002(2017),  
arXiv:1610.04545 [hep-lat].

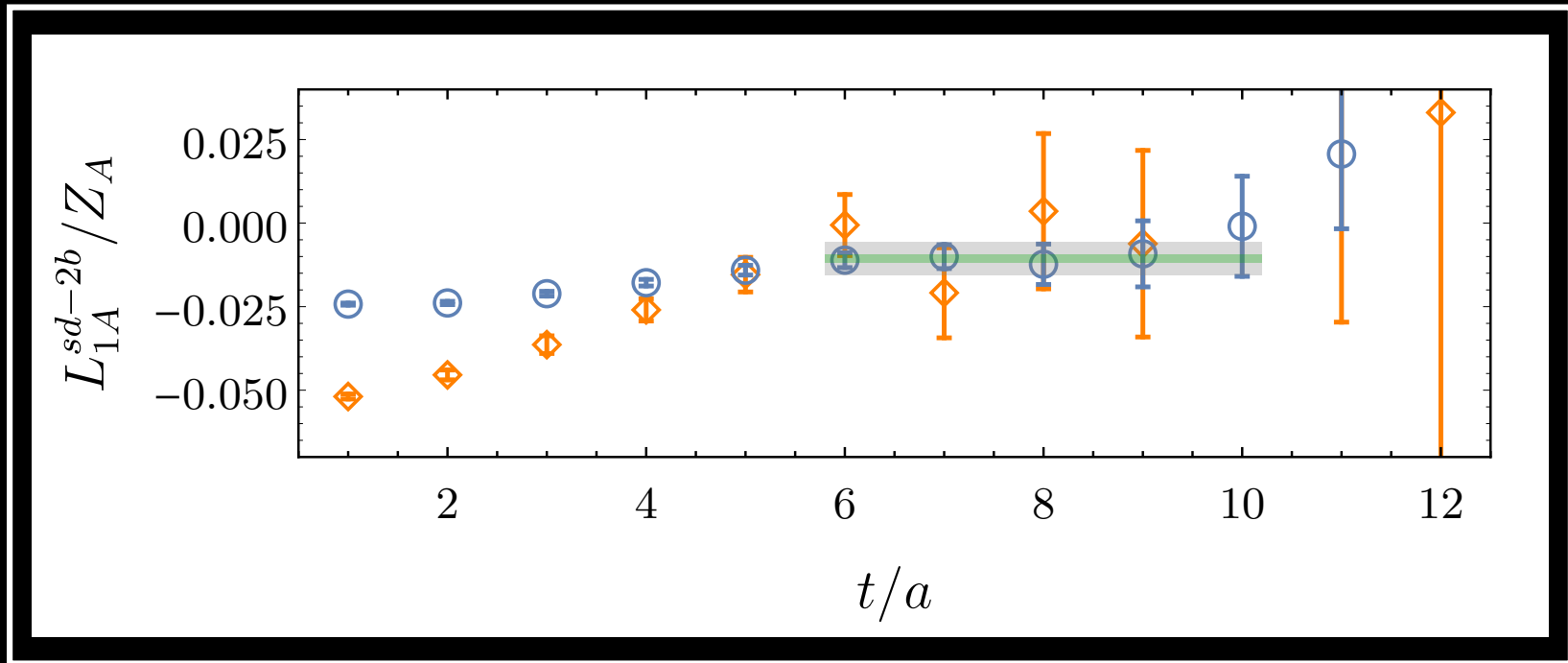
Detmold and Savage, Nucl.Phys.A743, 170 (2004)  
Briceno and ZD, Phys.Rev. D88, 094507 (2013)

# FIRST-ORDER RESPONSE TO AXIAL FIELD

$$\langle pp | A_3^+ | d \rangle$$



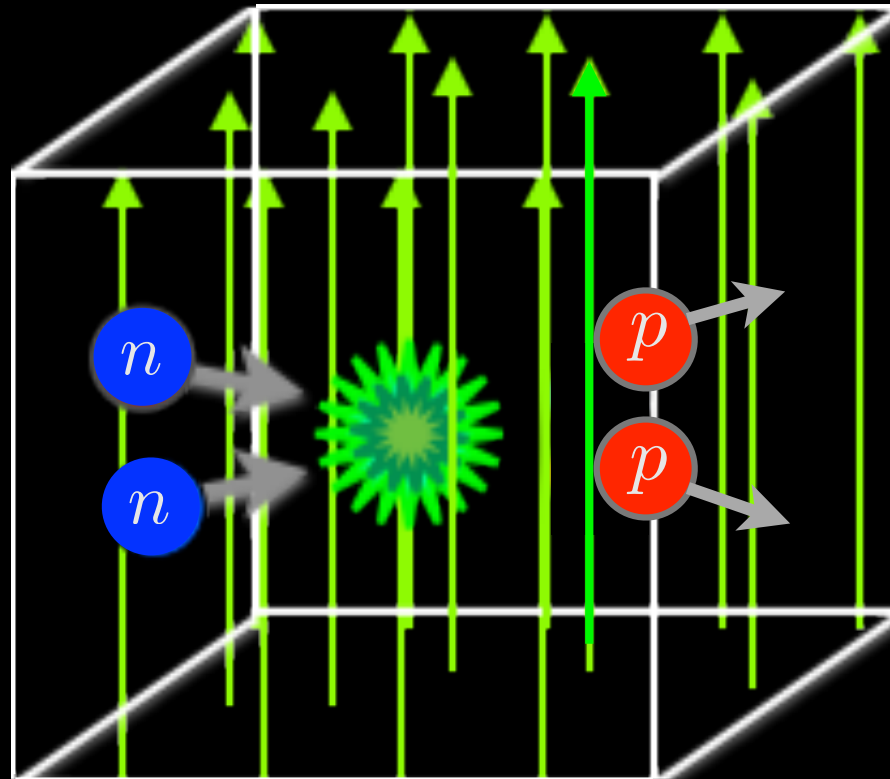
@  $m_\pi \approx 800$  MeV



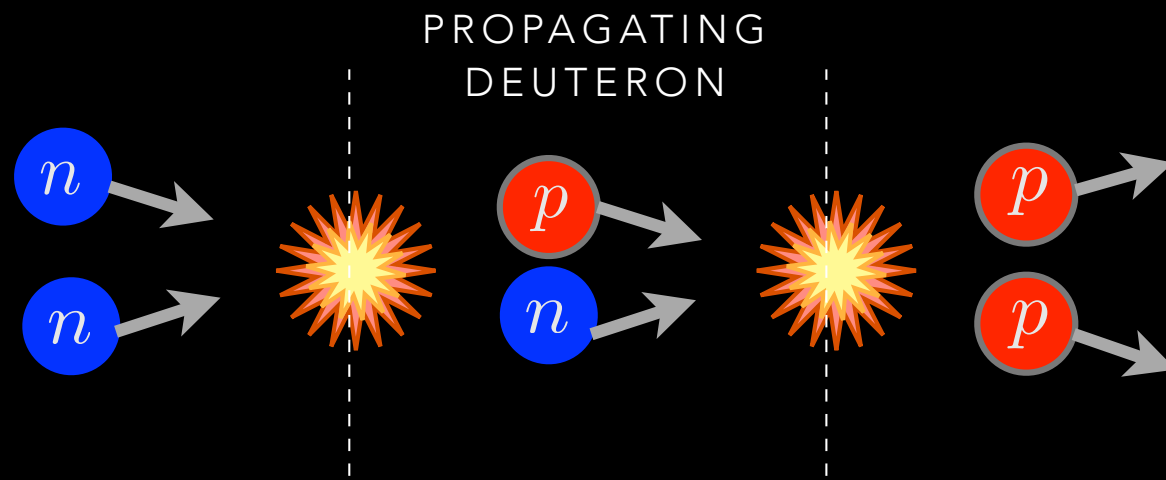
$$L_{1,A}^{sd-2b} \equiv \frac{|\langle pp | A_3^+ | d \rangle| - g_A}{Z_A} = -0.011(01)(15)$$

$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9) \text{ fm}^3 \quad @ \quad \mu = m_{\pi}^{\text{phys.}} = 140 \text{ MeV}$$

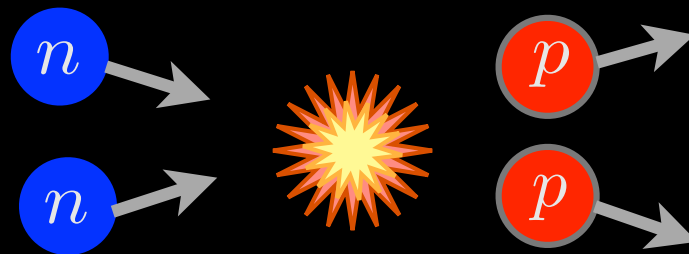
# SECOND-ORDER RESPONSE TO AXIAL FIELD



Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos, Savage, Shanahan (NPLQCD collaboration), [arXiv:1610.04545 \[hep-lat\]](#), [arXiv:1701.03456 \[hep-lat\]](#), [arXiv:1702.02929 \[hep-lat\]](#).



LONG-DISTANCE PIECE



SHORT-DISTANCE PIECE

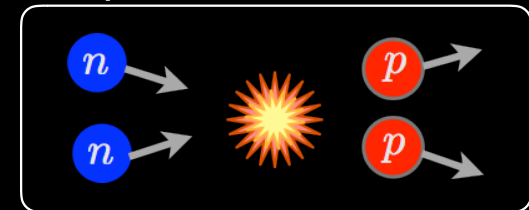
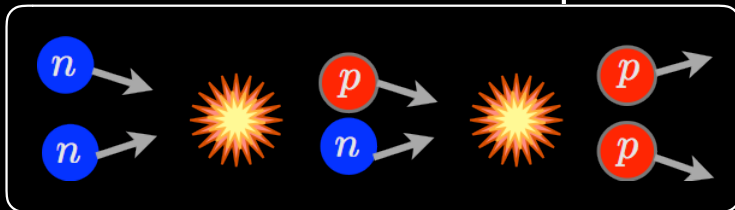
# SECOND-ORDER RESPONSE TO AXIAL FIELD FROM LQCD

$$\mathcal{R}_{nn \rightarrow pp}(t) = \frac{C_{nn \rightarrow pp}(t)}{2C_{0;0}^{(nn)}(t)}$$

LONG-DISTANCE  
CONTRIBUTION

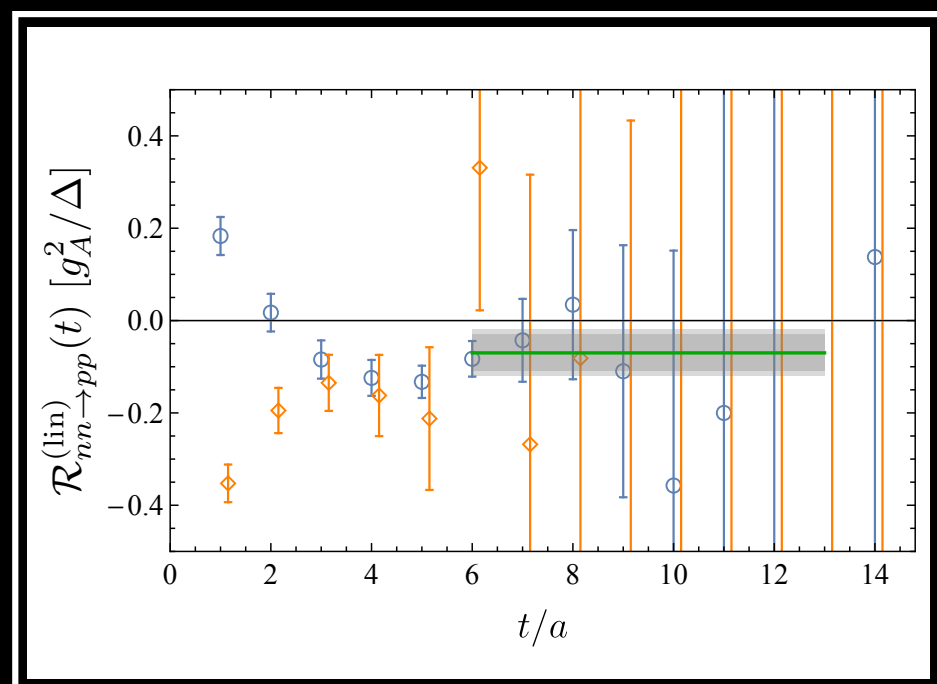
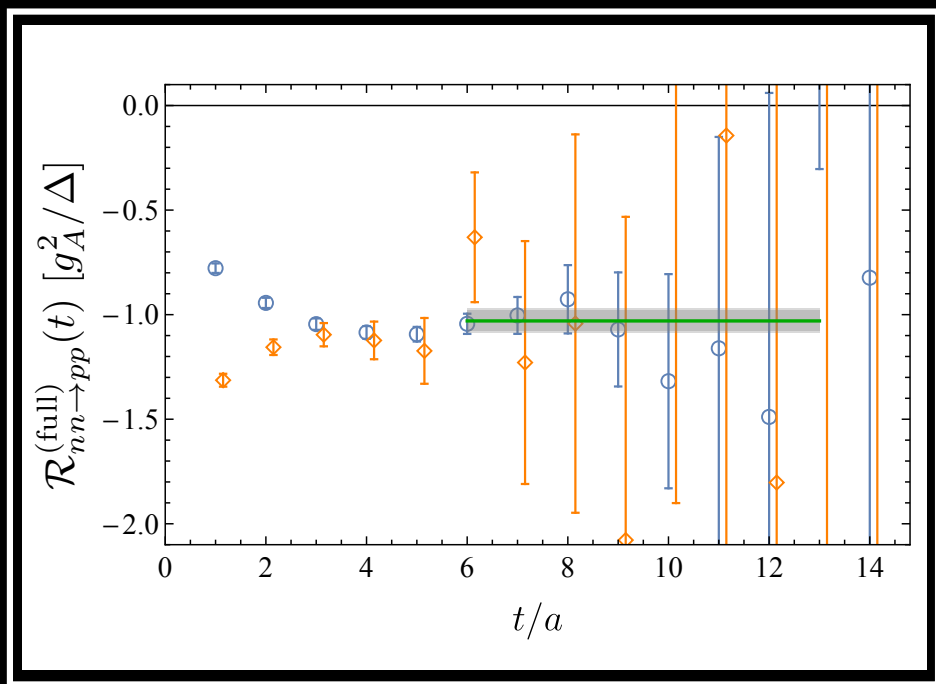
SHORT-DISTANCE  
CONTRIBUTION

$$a^2 \mathcal{R}_{nn \rightarrow pp}(t) = \left[ -t + \frac{e^{\Delta t} - 1}{\Delta} \right] \frac{\langle pp | \tilde{J}_3^+ | d \rangle \langle d | \tilde{J}_3^+ | nn \rangle}{\Delta} + t \sum_{l' \neq d} \frac{\langle pp | \tilde{J}_3^+ | l' \rangle \langle l' | \tilde{J}_3^+ | nn \rangle}{\delta_{l'}} + C + D e^{\Delta t} + \mathcal{O}(e^{-\delta t}, e^{-\delta' t})$$

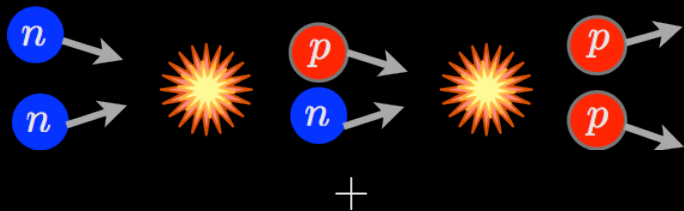


# SECOND-ORDER RESPONSE TO AXIAL FIELD FROM LQCD

$$\langle pp | A_3^+ A_3^+ | nn \rangle \quad @ \quad m_\pi \approx 800 \text{ MeV}$$



LONG-DISTANCE CONTRIBUTION



SHORT-DISTANCE CONTRIBUTION



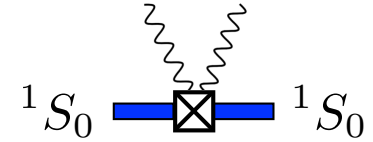
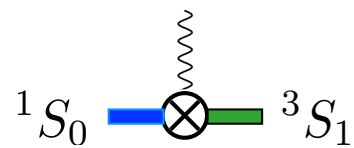
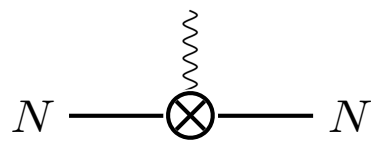
SHORT-DISTANCE CONTRIBUTION



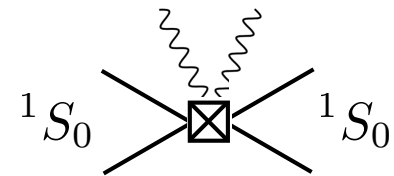
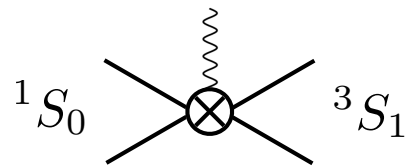
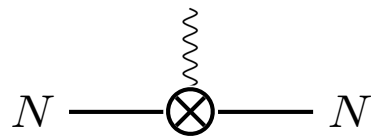
# HOW CAN LATTICE QCD FINDINGS BECOME USEFUL TO NUCLEAR MANY-BODY CALCULATION?

Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos, Savage, Shanahan (NPLQCD collaboration),  
[arXiv:1610.04545 \[hep-latt\]](#), [arXiv:1701.03456 \[hep-lat\]](#), [arXiv:1701.03456 \[hep-lat\]](#), [arXiv:1702.02929 \[hep-lat\]](#).

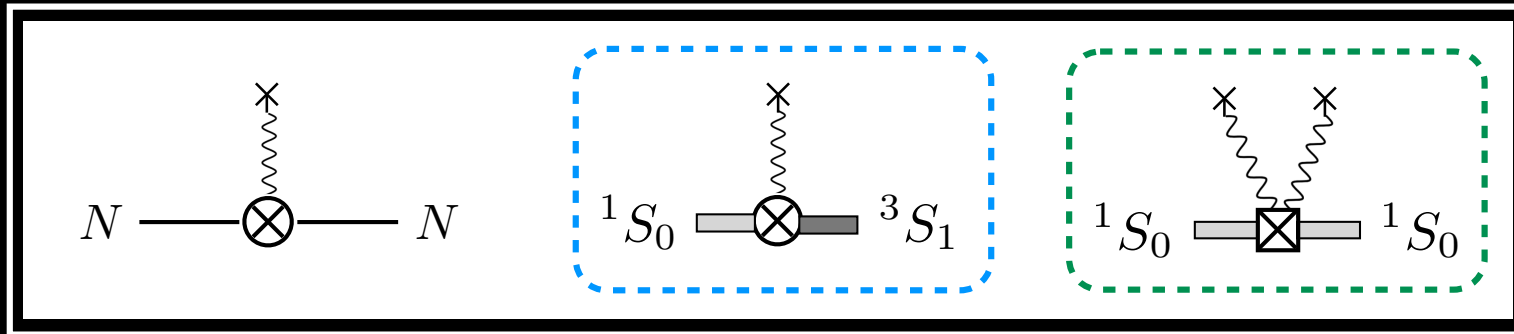
# DOUBLE-BETA DECAY AND EFT



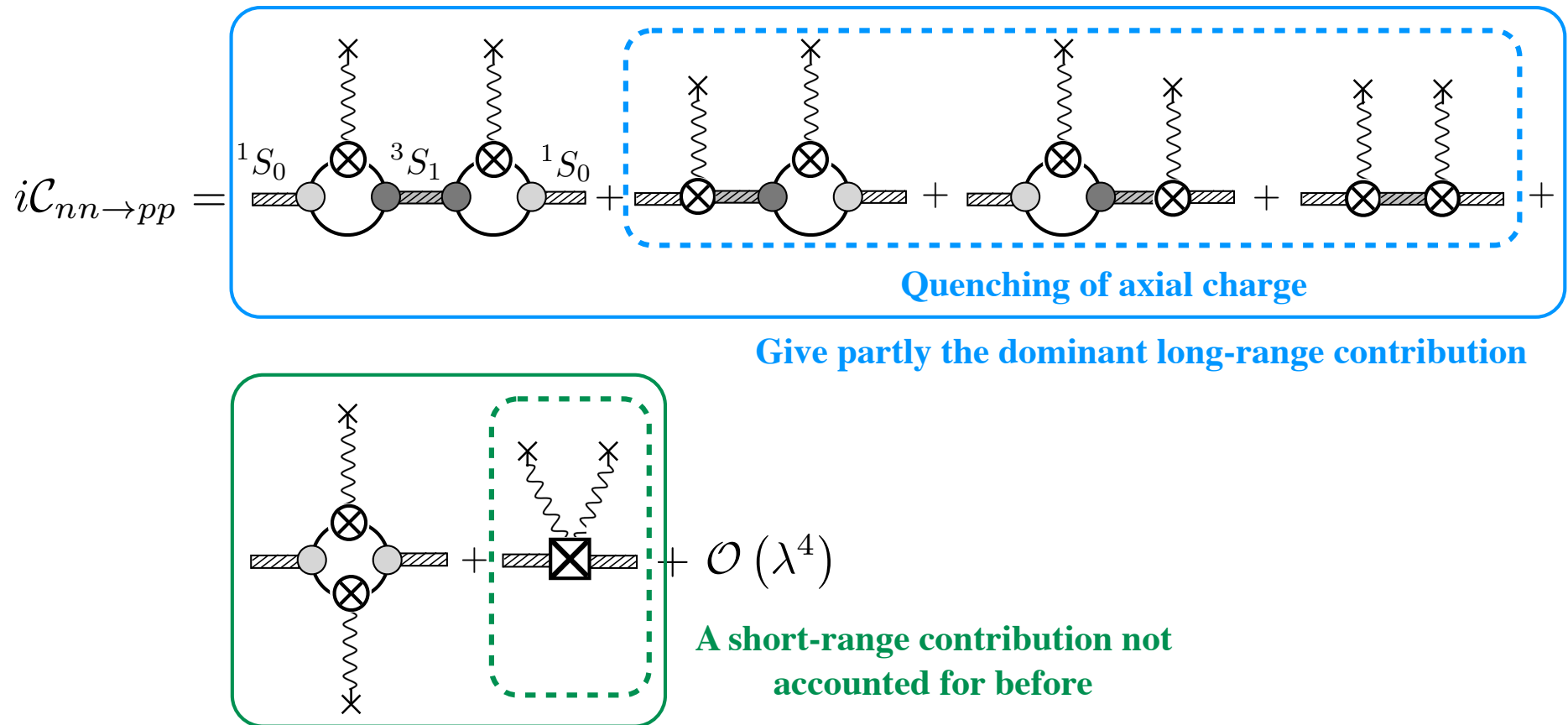
OR



# EFT VERTICES



## EFT CORRELATION FUNCTION

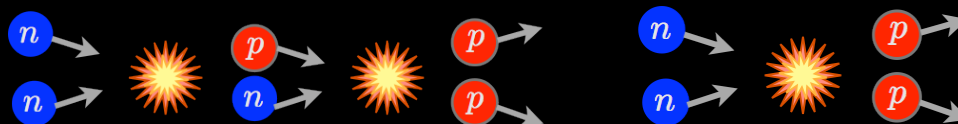


## SECOND-ORDER RESPONSE TO AXIAL FIELD FROM EFT

$$M_{pp \rightarrow d} = g_A(1 + S) + \mathbb{L}_{1,A}$$

AND

$$M_{nn \rightarrow pp} = -\frac{|M_{pp \rightarrow d}|^2}{\Delta} + \frac{M g_A^2}{4\gamma_s^2} - \mathbb{H}_{2,S}$$



$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8) \text{ fm}$$

$$@ m_\pi \approx 800 \text{ MeV}$$

LESSON FROM 800 MEV WORLD:

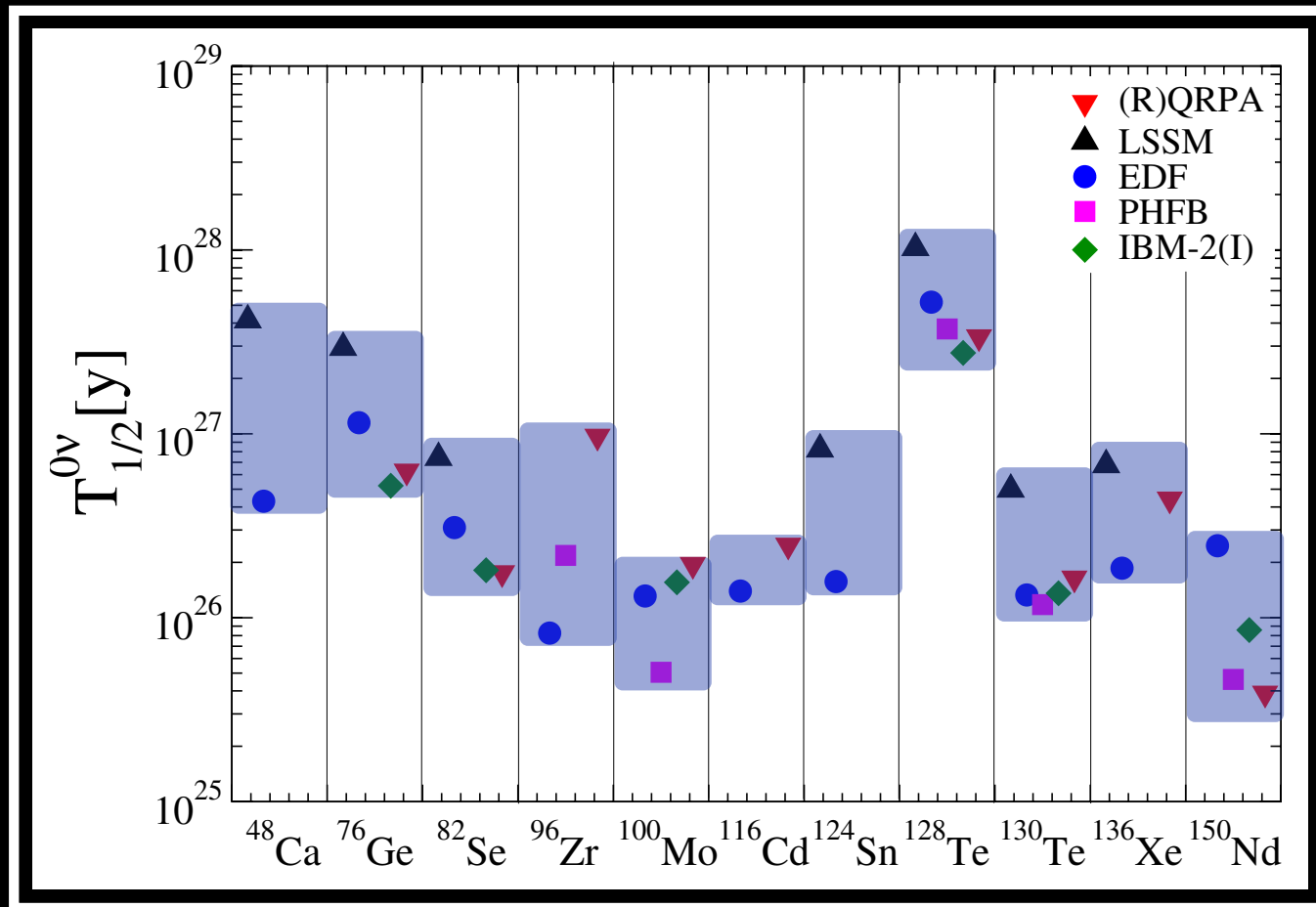
AXIAL POLARIZABILITY COULD BE IMPORTANT. CANNOT BE CONSTRAINED BY SINGLE-BETA DECAY PROCESSES.

# CURRENT STATUS OF NUCLEAR MATRIX ELEMENTS

DECAY RATE

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

NUCLEAR MATRIX ELEMENT IN LIGHT  
NEUTRINO EXCHANGE SCENARIO



Avignone, Elliott and Engel, REVIEWS OF MODERN PHYSICS, VOLUME 80 (2008)

Vergados, Ejiri and Simkovic, Rep. Prog. Phys. 75 106301 (2012)

Menendez, Gazit, and Schwenk, Phys.Rev.Lett.107, 062501 (2011)

WHAT IS NEXT FOR US?

# NUMERICALLY EVALUATING A QCD FOUR-POINT CORRELATION FUNCTION

LATTICE NEUTRINO PROPAGATOR IN  
POSITION SPACE - INSERT BY HAND

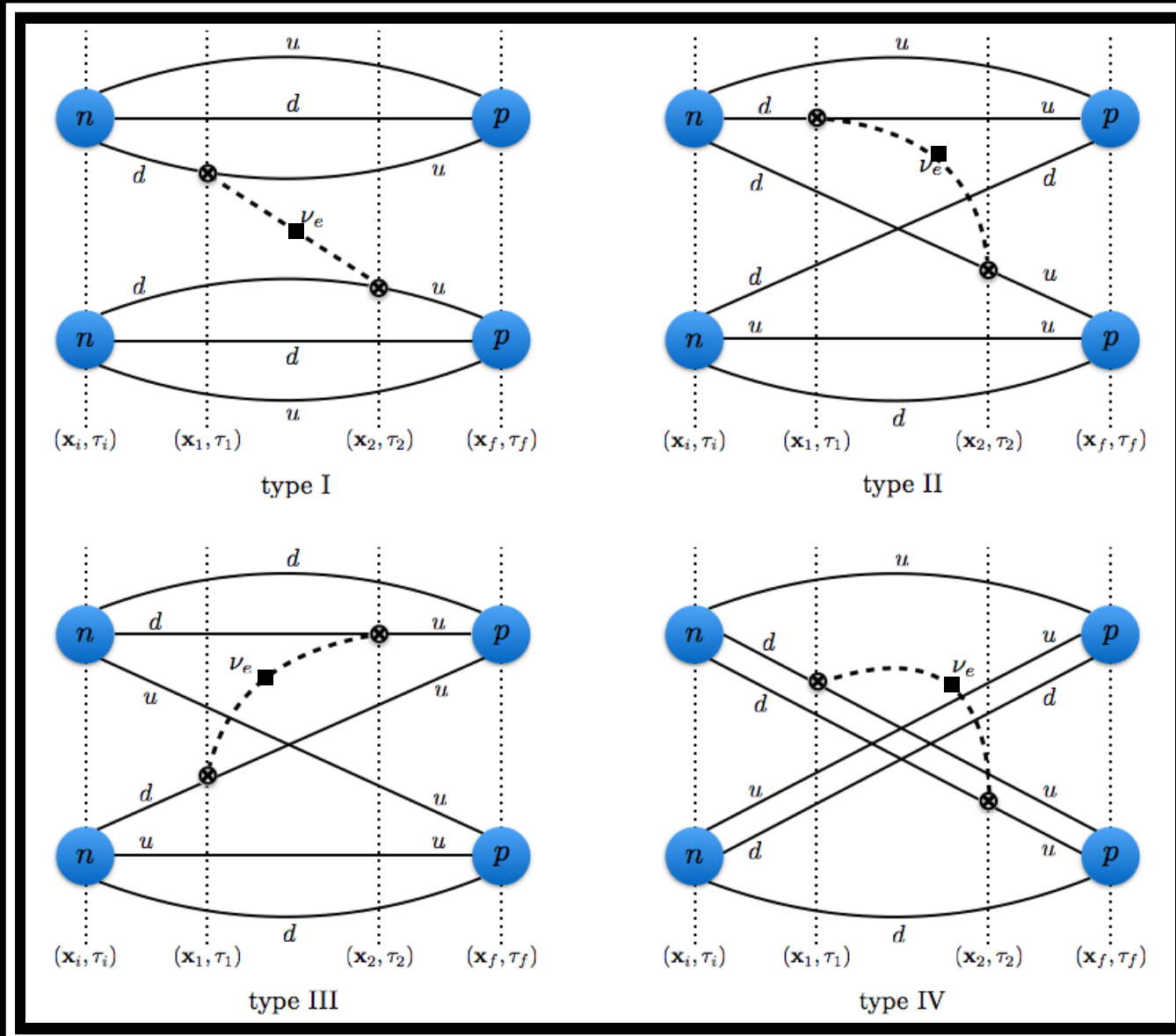
$$C_{nnpp(ee)}^{latt}(\tau_i, \tau_1, \tau_2, \tau_f; \mathbf{p}', \mathbf{p}, \mathbf{k}_1, \mathbf{k}_2) = \sum_{\mathbf{x}_i, \mathbf{x}_f} e^{i\mathbf{p}' \cdot \mathbf{x}_i - i\mathbf{p} \cdot \mathbf{x}_f} \sum_{\mathbf{x}_1, \mathbf{x}_2} S_\nu(x_1, x_2) \times$$

$$\left\{ \theta(\tau_1 - \tau_2) e^{ik_1 \cdot x_1 + ik_2 \cdot x_2} \langle 0 | \mathcal{O}_{pp}(\mathbf{x}_f, \tau_f) J_\alpha^+(\mathbf{x}_1, \tau_1) J_\beta^+(\mathbf{x}_2, \tau_2) \mathcal{O}_{nn}^\dagger(\mathbf{x}_i, \tau_i) | 0 \rangle + \right. \\ \left. \theta(\tau_1 - \tau_2) e^{ik_2 \cdot x_1 + ik_1 \cdot x_2} \langle 0 | \mathcal{O}_{pp}(\mathbf{x}_f, \tau_f) J_\alpha^+(\mathbf{x}_1, \tau_1) J_\beta^+(\mathbf{x}_2, \tau_2) \mathcal{O}_{nn}^\dagger(\mathbf{x}_i, \tau_i) | 0 \rangle \right\}$$

INTERPOLATING  
FIELDS FOR NN STATES

QUARK-LEVEL CURRENTS

PICTORIALLY:

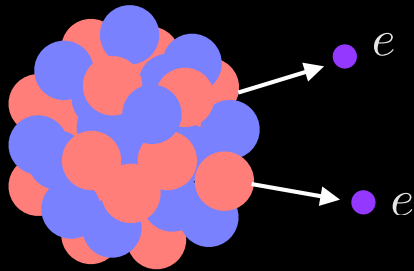


MORE RESULTS ON THEORY AND  
COMPUTATION SOON...

# TO SUMMARIZE...

THE GOAL OF NUCLEAR PHYSICS RESEARCH IS TO PROVIDE RELIABLE PREDICTIONS FOR COMPLEX PHENOMENA IN NATURE AND TO HELP ISOLATE NEW INTERACTIONS.

A FIRST-PRINCIPLES APPROACH TO NP BASED ON QCD IS POSSIBLE. TO CONNECT TO MANY-BODY CALCULATIONS EFTS ARE NEEDED.



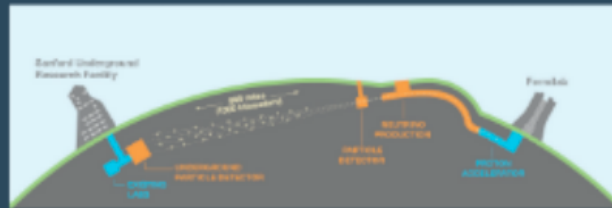
I PRESENTED ONE SUCH PATH TO OBTAIN NUCLEAR MATRIX ELEMENTS IN BB DECAYS.

SHORT-DISTANCE CONTRIBUTIONS (AXIAL POL.) MAY BE IMPORTANT IN BI-LOCAL MATRIX ELEMENT FOR NN TO PP.

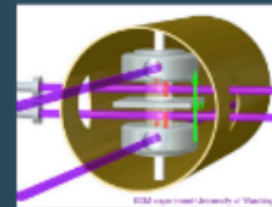
# MORE IN THIS DIRECTION...

- Nuclear matrix elements for tests of fundamental symmetries in nature such as EDM, neutrino/nucleus interactions, and searches for BSM physics such as in  $0\nu\beta\beta$ .

GERDA



DUNE



EDM-UW

Chang, ZD, Detmold, Gambhir, Orginos, Parreno, Savage, Shanahan, Wagman and Winter, accepted for publication in PRL (2018), arXiv:1712.03221 [hep-lat]

- QCD spectrum and Exotics / The role of gluons in nuclear structure for EIC / Nucleon and nucleus parton distribution functions



EIC



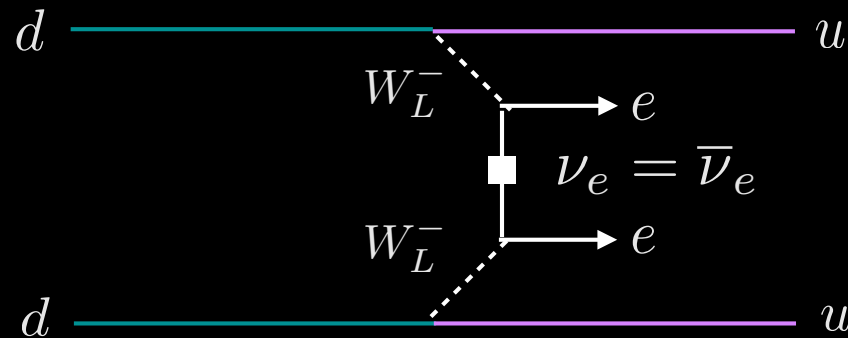
JLab 12GeV upgrade

Winter, Detmold, Gambhir, Orginos, Savage, Shanahan and Wagman, First lattice QCD study of the gluonic structure of light nuclei, Phys. Rev. D 96, 094512 (2017).

THANK YOU

BACKUP SLIDES

# POSSIBLE SCENARIOS: NOT FAR FROM THE STANDARD MODEL: LIGHT NEUTRINO EXCHANGE



REQUIRES JUST A LITTLE BIT OF DEVIATION FROM STANDARD MODEL

- $$\mathcal{L}_M = -\frac{m_L}{2} [(\overline{\nu_L})^c \nu_L + \text{h.c.}] - \frac{m_R}{2} [(\overline{\nu_R})^c \nu_R + \text{h.c.}]$$

Majorana (1937)
- Leading dimensions 5 interaction:

$$\frac{1}{\Lambda} \overline{\nu^c} \nu H H$$

Weinberg (1979)

CAN EVEN ADD A DIRAC MASS TERM WITH NO NEED TO A BIG FINE TUNING

- $$\mathcal{L}_D = -m_D (\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L)$$

The Yukawa interaction:  $Y_\nu \overline{\nu_L} \nu_R H$

THANKS TO THE SEESAW MECHANISM

Gell-Mann et al. (1979); Yanagida (1979);  
Mohapatra and Senjanovic (1980)

$$\mathcal{M} = \begin{pmatrix} m_L & m_D^T \\ m_D & m_R \end{pmatrix} \rightarrow m_l \approx -\frac{m_D^2}{m_R}, \quad M_h \approx m_R \rightarrow m_R \gg 1 \text{ TeV}$$

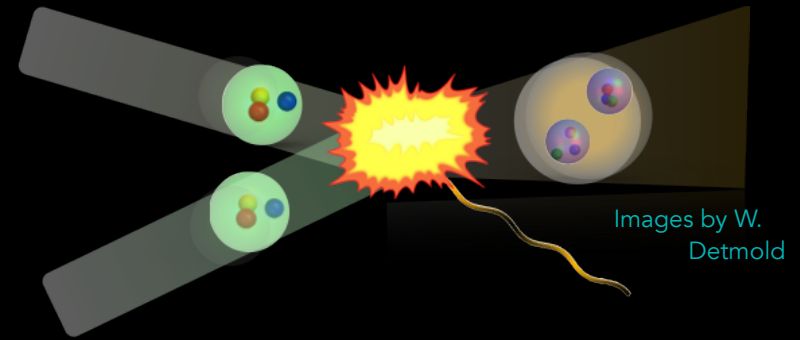
# PP FUSION FROM POINTLESS EFT

Butler and Chen, Nucl.Phys., A675, 575 (2000)

Butler, Chen, and Kong, Phys.Rev., C63, 035501 (2001)

Butler and Chen, Phys.Lett., B520, 87 (2001)

Savage, Shanahan, Tiburzi, Wagman, Winter, Beane, Chang, ZD, Detmold and Orginos, (NPLQCD collaboration), Phys.Rev.Lett.119,062002(2017), arXiv:1610.04545 [hep-latt].



Images by W.  
Detmold

$$\Lambda(0) = \frac{1}{\sqrt{1-\gamma\rho}} \{e^\chi - \gamma a_{pp} [1 - \chi e^\chi \Gamma(0, \chi)] + \frac{1}{2} \gamma^2 a_{pp} \sqrt{r_1 \rho}\} - \frac{1}{2g_A} \gamma a_{pp} \sqrt{1-\gamma\rho} \quad L_{1,A}^{sd-2b}$$

$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9) \text{ fm}^3 \quad @ \quad \mu = m_\pi^{\text{phys.}} = 140 \text{ MeV}$$

